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CYCLISTS' ROAD SAFETY -

DO BICYCLE TYPE, AGE AND INFRASTRUCTURE CHARACTERISTICS MATTER?

DISSERTATION

zur Erlangung des akademischen Grades doctor rerum naturalium (Dr. rer. nat)

vorgelegt der Fakultät für Human- und Sozialwissenschaften
der Technischen Universität Chemnitz

KATJA SCHLEINITZ

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ZUSAMMENFASSUNG

In den letzten Jahren hat die Verbreitung von Elektrofahrrädern, sogenannten Pedelecs, stark zugenommen. Dies ist vor dem Hintergrund der Umweltfreundlichkeit und Gesundheitsförderlichkeit dieser Form der Fortbewegung zunächst grundsätzlich positiv zu bewerten. Gleichzeitig besteht jedoch die Sorge, dass Elektrofahrradfahrer häufiger und in schwerere Unfälle verwickelt werden könnten als Fahrradfahrer. So bieten motorgestützte Elektrofahrräder das Potential, höhere Geschwindigkeiten zu erreichen als konventionelle Fahrräder, und werden zudem vor allem von älteren Verkehrsteilnehmern genutzt. Nicht zuletzt deswegen könnten sich durch diese neue Mobilitätsform auch neue Herausforderungen für die Verkehrs-, insbesondere Radinfrastrukturen ergeben. Tatsächlich jedoch blieben die Auswirkungen auf die Verkehrssicherheit bisher weitestgehend ungeklärt. Um dieser Problematik zu begegnen, wurde im Rahmen einer Naturalistic Cycling Studie (NCS) und mehreren experimentellen Untersuchungen folgenden Fragen nachgegangen: Fahren Elektrofahrradfahrer tatsächlich schneller als nicht-motorisierte Radfahrer? Wie wirken sich diese potentiell höheren Geschwindigkeiten darauf aus, wie Elektrofahrradfahrer von Autofahrern wahrgenommen werden? Welchen Einfluss hat das Alter der Radfahrer auf die Geschwindigkeiten und auch auf deren Neigung zu Unfällen bzw. sicherheitskritischen Situationen im Verkehr? Und welchen Einfluss hat die Infrastruktur auf die gewählten Geschwindigkeiten und die Auftretenshäufigkeit von kritischen Situationen? Diese und weitere Fragen wurden in insgesamt vier Arbeiten, die in internationalen Fachzeitschriften publiziert sind (I - IV), beleuchtet.

Im ersten Artikel werden die Geschwindigkeiten von Fahrradfahrern (n = 31) im Gegensatz zu Pedelecfahrern (n = 49; Motorunterstützung bis 25 km/h) sowie S-Pedelecfahrern (n = 10; Motorunterstützung bis 45 km/h) betrachtet. Als Einflussgrößen wurden das Alter und die Nutzung verschiedener Infrastrukturtypen der Probanden ausgewertet. Alle Räder wurden mit einem Datenaufzeichnungssystem inklusive Kameras und Geschwindigkeitssensoren ausgestattet, um für vier Wochen ein Bild des natürlichen Fahrverhaltens zu erhalten. Unabhängig von der Infrastruktur waren S-Pedelecfahrer schneller unterwegs waren als Fahrrad- und Pedelecfahrer. Pedelecfahrer fuhren ebenfalls signifikant schneller als konventionelle Fahrradfahrer. Die höchsten Geschwindigkeiten wurden für alle Radtypen auf der (mit dem motorisierten Verkehr geteilten) Fahrbahn sowie der Radinfrastruktur gemessen. Das Alter der Fahrer hatte ebenfalls einen signifikanten Einfluss auf die Geschwindigkeit: Unabhängig vom Fahrradtyp waren ältere Fahrer (65 Jahre und älter) deutlich langsamer als Probanden jüngerer

Altersgruppen (41-64 Jahre sowie 40 Jahre und jünger). Die beiden jüngeren Altersgruppen fuhren selbst ohne Motorunterstützung (konventionelles Fahrrad) schneller als die älteren Pedelecfahrer. Genauere Analysen (wie etwa das Verhalten beim Bergabfahren) legen nahe, dass dieser Befund nicht allein der physischen Leistungsfähigkeit zugeschrieben werden kann. Es scheint vielmehr so, als ob ältere Fahrrad- und Elektroradfahrer durch die geringere Geschwindigkeit versuchen, Defizite in der Reaktionsgeschwindigkeit auszugleichen bzw. generell vorsichtiger fahren.

Der zweite Artikel beschäftigt sich mit der Frage, inwieweit sich die Art und Häufigkeit von Unfällen und kritischen Situationen bei den drei verschiedenen Altersgruppen unterscheiden. Auch hier wurde auf die Daten aus der NCS zurückgegriffen, auf deren Basis eine umfassende Videokodierung durchgeführt wurde. Es zeigten sich keine Unterschiede zwischen den Altersgruppen hinsichtlich des Auftretens kritischer Situationen; weder in Bezug auf die absolute Anzahl, noch gemessen an der relativen Häufigkeit (pro 100 km). Ebenfalls keine Zusammenhänge fanden sich zwischen dem Alter der Fahrer und der Art von Konfliktpartnern oder der Tageszeit der kritischen Situationen. Auch hier scheint es so, dass Ältere keinem erhöhten Risiko unterliegen, und etwaige altersbedingte Einschränkungen kompensieren können. Bei der Betrachtung des Einflusses des Infrastrukturtyps auf das Auftreten von kritischen Situationen zeigte sich, dass, bezogen auf die zurückgelegten Wegstrecken, die Nutzung der mit dem motorisierten Verkehr geteilten Fahrbahn als relativ sicher einzustufen ist. Demgegenüber ergab sich ein erhöhtes Risiko für Unfälle oder kritische Situationen auf designierter Radinfrastruktur. Dies widerspricht der Wahrnehmung vieler Radfahrer, die diese Infrastruktur als besonders sicher empfinden. Es ist allerdings anzunehmen, dass diese Wahrnehmung nicht nur auf der vermeintlichen Auftretenshäufigkeit, sondern auch auf dem angenommenen Schweregrad einer möglichen Kollision beruht.

Zwei weitere Artikel beschäftigen sich damit, wie Autofahrer die Geschwindigkeit beziehungsweise die Annäherung von Elektrofahrrädern wahrnehmen. Dies ist insbesondere in Kreuzungssituationen relevant, in denen Autofahrer abschätzen müssen, ob sie noch rechtzeitig vor einem Fahrrad abbiegen können ohne mit diesem zu kollidieren. Es wurde vermutet, dass die fehlende Erfahrung mit Elektrofahrrädern und der von ihnen erreichbaren Geschwindigkeit vermehrt zu entsprechenden Unfällen führen könnte. Der Frage wurde mit einem Experiment zur Lückenakzeptanz auf der Teststrecke (Artikel III) und einer Videostudie zu Schätzungen von Zeitlückengrößen (Artikel IV) nachgegangen. Es zeigte sich, dass Autofahrer die verbleibende Zeit bis zur Kollision für Elektrofahrradfahrer geringer einschätzten als für konventionelle Radfahrer. Zudem wählten Autofahrer bei einem herannahenden Elektrofahrrad signifikant kleinere Zeitlücken zum Abbiegen, als bei einem konventionellen Fahrrad. Dieser Effekt verstärkte sich

sogar noch, wenn die Geschwindigkeit des herannahenden Zweirades zunahm. Diese Befunde legen nahe, dass die Einschätzung der Geschwindigkeit beziehungsweise Annäherung von Elektrofahrrädern durchaus risikobehaftet ist.

Die Ergebnisse dieser Arbeit helfen dabei, die Auswirkungen der steigenden Verbreitung von Elektrofahrrädern auf die Verkehrssicherheit einzuschätzen. Auch erlauben es die Erkenntnisse, Maßnahmen zur Erhöhung der Verkehrssicherheit für Fahrrad- und Elektrofahrradfahrern aller Altersgruppen abzuleiten. Damit leistet diese Arbeit einen Beitrag zur Unterstützung einer sicheren, gesunden und umweltfreundlichen Mobilität.

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SYNOPSIS

1 Overview of the dissertation

Electric bicycles (e-bikes) are a relatively new form of transport. The aim of this dissertation is to investigate their effects on road safety. In 2012, at the beginning of this dissertation project, knowledge of e-bikes in general and their impact on road safety in particular was relatively scarce. As a starting point of this work, the influence of e-bikes on road safety was investigated compared relative to the road safety of conventional bicycles. Additionally, the influence of the age of the rider on safety is considered as a supplementary factor. Special attention is paid to the impact of the infrastructure utilised by riders and its characteristics. This cumulative dissertation consists of four research articles, labelled Paper I to IV accordingly. Papers I to IV have been published in peer reviewed journals. The synopsis provides an overview of previous research as well as a theoretical framework of the safety of cyclists and e-bike riders. Speed, and its perception through other road users (measured with experiments to gap acceptance and time to arrival (TTA) estimates) are considered as relevant factors for road safety. In Chapter 4, the research objectives are presented in detail. The methodology is clarified in Chapter 5, and in Chapter 6 and 7 the results are summarised and discussed. The implications of the results are considered in Chapter 8.

In Paper I, the differences in speed between bicycles, pedelecs (pedal electric cycle, motor assistance up to 25 km/h) and S-pedelecs (pedal electric cycle, motor assistance up to 45 km/h) were investigated. Additionally the influence of infrastructure type, road gradient and the age of the rider were taken into account. Paper II is concerned with the influence of different conflict partners in crashes, and the utilisation of infrastructure on the safety of cyclists. For this purpose, safety critical events (SCE) involving cyclists were examined, with a special focus on the differences between younger, middle aged, and older cyclists. Papers III and IV focus on the perception of speed of e-bike and bicycle riders through other road users and its implications for road safety. Paper III specifically deals with the gap acceptance of car drivers at intersections in the presence of cyclists and e-bike riders with different speeds and under varying conditions (e.g. at intersections with different road gradients). Paper IV looks at drivers TTA estimates of approaching bicycles and e-bikes in combination with other influencing factors (e.g. speed, cyclist age).

Paper I

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J. F., & Gehlert, T. (2015). The German Naturalistic Cycling Study - Comparing cycling speed of different e-bikes and conventional bicycles. *Safety Science.* Advance online publication. doi:10.1016/j.ssci.2015.07.027

Paper II

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J. F., & Gehlert, T. (2015). Conflict partners and infrastructure use in safety critical events in cycling - Results from a naturalistic cycling study. *Transportation Research Part F: Psychology and Behaviour, 31*, 99-111. doi:10.1016/j.trf.2015.04.002

Paper III

Petzoldt, T., Schleinitz, K., Krems, J. F., & Gehlert, T. (2015). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science***.** Advance online publication. doi: 10.1016/j.ssci.2015.07.021

Paper IV

Schleinitz, K., Petzoldt, T., Krems, J. F., & Gehlert, T. (2016). The influence of speed, cyclists' age, pedalling frequency, and observer age on observers' time to arrival judgements of approaching bicycles and e-bikes. *Accident Analysis and Prevention, 92,* 113-121. doi:10.1016/j.aap.2016.03.020

2 Introduction

Cycling is steadily gaining popularity. According to the OECD, (OECD/International Transport Forum, 2012) "Bicycles are an essential part of the urban mobility mix" (p. 1). They are an affordable mode of transport and a good alternative to cars or public transport, especially for short door-to-door trips (Bundesministerium für Verkehr und digitale Infrastruktur, 2014). Increased bicycle usage could improve the liveability of cities, especially because of their environmental advantages; they could help reduce both congestion and pollution. In addition, cycling increases health and fitness and reduces the costs of illness, disease and ageing (OECD/International Transport Forum, 2013). All of these facts contribute to the healthy image of cycling (Oxley, Corben, Fildes, O'Hare, & Rothengatter, 2004). These advantages could be some of the reasons why in Germany, in 2014, the number of bicycles increased from 71 to 72 million bicycles (Zweirad-Industrie-Verband, 2015a). This represents about 2.4 bicycles per household (Sinus, 2014).

Electric bicycles (e-bikes) are a relatively new mode of transport and are expected to further boost the popularity of cycling. Worldwide sales figures of e-bikes are expected to grow, in 2018 the total sales will be 18 million more than they were in 2012 (Pike Research, 2012), and e-bikes are particularly popular in China. (Bundesministerium für Verkehr Innovation und Technologie, 2013). Similar trends have been observed in Europe; in recent years, e-bike sales figures have increased (COLIBI & COLIPED, 2014), and are expected to increase even further (Jellinek, Hildebrandt, Pfaffenbichler, & Lemmerer, 2013). In 2014 Germany had the highest number of e-bike sales in Europe, with nearly half a million sold (COLIBI & COLIPED, 2014).

There are several reasons for the popularity of e-bikes, and previous studies investigated the advantages of e-bikes compared with conventional bikes. The reduced physical effort and increased speed of an e-bike were frequently mentioned, whilst participants also stated that it was easier to make longer trips and ride uphill on an e-bike (Chaloupka-Risser, Aichleitner, Wolf-Eberl, Ausserer, & Konecny, 2011; Kuratorium für Verkehrssicherheit, 2011; Schleinitz et al., 2014). Due to their motor assistance, e-bikes are also regarded as more comfortable for the transport of children and goods than conventional bicycles. Other stated advantages of e-bikes also apply to conventional bicycles, including the avoidance of traffic jams or searching for a parking lot. E-bikes are also considered as an affordable alternative to a second car, which gives reason to believe that e-bikes could be used to help reduce short car journeys (Popovich et al., 2014; Wolf & Seebauer, 2014). Disadvantages of e-bikes reported in the literature include their relatively heavy weight, the limited battery capacity, and the high initial costs compared to conventional bicycles (Chaloupka-Risser et al., 2011; Schleinitz et al., 2014). It is suspected that e-bikes are more failure-prone than bicycles and they may therefore need more maintenance (Chaloupka-Risser et al., 2011; Kuratorium für Verkehrssicherheit, 2011). E-bike riders were also concerned about the risk of thefts (Dill & Rose, 2012; Popovich et al., 2014). Other disadvantages of e-bikes concern road safety; they were considered as dangerous because of the high speed the rider can reach with the support of the motor (Chaloupka-Risser et al., 2011), and severe crashes and injuries were feared (Popovich et al., 2014). To understand these concerns, the safety of e-bikes - in comparison to conventional bicycles - will be considered in this dissertation.

It is also important to consider the different user groups. Data show that frequent e-bike users include commuters and service providers, such as pizza delivery men or postmen, who make use of e-bikes on a daily basis (BUWAL Bundesamt für Umwelt Wald und Landschaft, 2004; elektrofahrrad.de, 2015). Another important user group is elderly people (Wolf & Seebauer, 2014). In a survey conducted in 2014, over the half of the respondents, aged 50 years old and older, stated to prefer riding an e-bike to a conventional bicycle (Sinus, 2014). In recent years, interest in e-bikes amongst younger riders increased slightly (Sinus, 2014), but it will nevertheless take some time for e-bikes to make a breakthrough in younger rider groups. Alrutz (2013) verified that most e-bike users rode a conventional bicycle before they bought an electric one. Those who had not cycled for a long time were particularly likely to have bought an electric model.

3 Road safety

Improved road safety is an important goal of the European Union; their "Vision Zero" set a goal of zero fatalities from road transport in 2050 (European Union, 2011). That figure also includes cyclists which are vulnerable road users. However, it is not only the reduction of fatalities but also the number of injuries of cyclists and their severity that should be decreased. To reach this goal, it is necessary to act on the factors which influence the risk of a crash. In the following sub-sections, two different frameworks, a more theoretical, the "Task-Capability Interface Model" (Fuller, 2005) and a more analytical approach the "Three traffic safety pillars" (Schepers, Hagenzieker, Methorst, Van Wee, & Wegman, 2014), will be considered, both of which are concerned with these factors and the relationships between them.

3.1 Task-Capability Interface (TCI) Model

In the past, different approaches were used to explain why crashes and collisions occur. One influential model was proposed by Fuller (2005), which focuses especially on collisions caused by drivers. In the TCI model, the difficulty of the driving task is the central factor in the development of crashes or collisions. According to the TCI model, a high task difficulty could lead to a loss of control of the vehicle and consequently to a crash. The difficulty of the driving task is influenced by the dynamics between the capability of the driver to deal with the situation and the demands of the task. The demands of the task can be influenced by other road users, including features of the vehicle as well as characteristics of the infrastructure. Additionally, decisions taken by the driver can have an effect on the demands of the task. The TCI model built on previous models, which define the driving task in hierarchical levels (Hollnagel, Nåbo, & Lau, 2003; Michon, 1985). A common assumption of these models is that a decision making process is required by the driver; he is the one taking operational, manoeuvring and strategic decisions. Fuller (2005) pointed out that these levels were considered as influencing factors on the demands of the task in the TCI model as well. Thus these previous models provide a more general view. However, Fuller's TCI Model goes one step further. It explains the development of collisions not only by considering the task demands inclusive the different decision levels, but also takes into account the capability of the driver. If the demands of the situation exceed the driver's capability, then the driving task will be too difficult, which could cause undesired consequences in terms of road safety.

The TCI model was first applied to drivers, but it can be applied to other road users such as cyclists as well. Different factors might affect the demands and hence the task difficulty. At this point, the influence of speed is a particularly important consideration. According to Fuller (2005), speed is a crucial factor of task difficulty. He argued that "it is self-evident that the faster a driver travels, the less time is available to take information in, process it and respond to it" (S. 464). Therefore, a higher speed might lead to a higher risk of loss of control of a vehicle, and ultimately, to a subsequent crash. Cycling too fast can have such negative consequences, too, especially in cases where the road surface is poor. Age related declines in physical fitness, and, as a consequence, a decline in the ability to perform the riding task, might add to this problem (Hagenzieker, 1996). When excessive speed and a reduced capability to perform the riding task are combined, then a small incident such as hitting a pothole or the sudden emergence of a pedestrian could be enough to cause a crash. But, at the same time, cycling too slowly can have adverse effects as well, because it can make the bicycle unstable. It is obvious that, as far as maintaining stability of the vehicle is concerned, this aspect of the riding task is more demanding than it is for a car driver.

A further aspect to be considered is the use of different types of infrastructure by cyclists (Schleinitz et al., 2014). In some cases, especially where there is less structure and regulation, there might be a mixture of different road users. The more different road users there are on the same infrastructure, the more confusing, and ultimately demanding the situation becomes, such that it could easily exceed the capabilities of the rider.

When it comes to e-bikes, an understanding of this theoretical background is especially important. In comparison with conventional bikes, riding an e-bike can be more demanding, especially due to the possibility of reaching a higher speed. Fuller, McHugh and Pender (2008) claimed that the prevention of collisions at higher speeds is more challenging. Besides, as mentioned in Chapter 2, e-bikes are particularly popular among the elderly; older cyclists often have reduced capabilities (Hagenzieker, 1996) such as slower reactions (Vlakveld et al., 2015) and more physical limitations (Ortlepp, 2013). Thus, one can expect older cyclists to have problems in managing certain situations compared to their younger counterparts; the demands of a traffic situation can more easily exceed their physical or mental capacities. Together with the higher speeds which are possible on e-bikes, this can be a dangerous mix.

3.2 Three traffic safety pillars

Whilst the TCI model is more of a theoretical framework to explain the crash risk of e-bike riders and cyclists, the so called *three traffic safety pillars* represent a more analytical approach. Crash risk is determined by the interaction of the three traffic safety pillars: the vehicle, the road user and the infrastructure (Othman, Thomson, & Lannér, 2009; Schepers, Hagenzieker, et al., 2014). Each of these three factors can influence each other, and the product of their interaction has an impact on the risk of cyclists being involved in a crash (Schepers, Hagenzieker, et al., 2014). As mentioned previously, they are also influencing factors on task demands in the TCI model. In order to better understand how each of these elements influence crash risk, the following sections will provide a literature review about the vehicle, the characteristics of the road user, and the infrastructure characteristics which influence road safety from a cycling perspective.

Chapter 3.3 will explore how vehicle characteristics and respective embedded systems have an effect on crash risk. In cars, advanced driver assistance systems can help to prevent crashes. However, bicycles lack such safety systems at the moment which could contribute to a high crash risk for cyclists. Additionally, it is unclear how new types of bicycles, such as e-bikes, change the crash risk of a rider in comparison to that of a conventional cyclist.

Furthermore, Chapter 3.4 will present evidence on how the skills and capabilities of the road user can impact the whole system. Functional changes because of ageing, such as reduced perception and a slower psychomotor response can increase the risk of crashes (Oxley et al., 2004). This might be a particular problem for cyclists, because, as mentioned previously, no systems have yet been developed which help compensate for these factors.

The characteristics of the infrastructure and the environment, and the way they have an impact on the risk of crashes will be presented in Chapter 3.5. The nature of the infrastructure plays an important role, especially for cyclists, because they use many different types of infrastructure. Also, the quality of the infrastructure (including, for example, potholes) has a direct effect on cyclists and influences the risk of crashes.

The three traffic safety pillars of the road user (and their capabilities), the vehicle, and the infrastructure are central factors in the TCI Model, and they all have an effect on the demands of the task. Therefore, these aspects will be particularly considered in the following Chapters (3.3-3.5). Firstly, the safety of two vehicles types (conventional bicycles and e-bikes) will be taken into account. Secondly, a closer look will be taken at the safety of elderly people, as a significant user group of e-bikes. Following this, the influence of infrastructure on the safety of riders will be addressed.

3.3 Vehicle: Road safety of bicycle and e-bike riders

It is important to have an idea of what people do with a conventional bike in order to make good comparisons with e-bikes. Thus, for a better evaluation of the road safety of e-bikes, the road safety of conventional bicycles is also considered. Crash statistics for conventional bicycles have been reported for longer than those for e-bikes. In recent years, the number of crashes involving conventional cyclists has not changed considerably. After car drivers, cyclists are the road users most frequently involved in crashes (Statistisches Bundesamt [Destatis], 2015a). Compared with the previous year, the fatality rate of cyclists slightly increased in 2014 (Statistisches Bundesamt [Destatis], 2015b), indicating that cyclists are still very much at risk. Because they are more vulnerable, cyclists are more likely to be injured in a crash than some other road users. Statistics from 2014 reveal that, in absolute terms, only car drivers suffered more injuries in the case of an accident than cyclists (Statistisches Bundesamt [Destatis], 2015c).

According to crash statistics, a considerable proportion (nearly 80%) of bicycle crashes involved another road user. In nearly three-quarters of the cases, the conflict partner was a car; others mainly involved other cyclists or pedestrians (Statistisches Bundesamt [Destatis], 2014a). In-depth analysis (e.g. GIDAS, SafetyNet) where a relatively small sample of crashes was assessed in detail (e.g. Orsi, Ferraro, Montomoli, Otte, & Morandi, 2014; Otte, Jänsch, & Haasper, 2012; SafetyNet, 2009), showed a similar picture: 80% of the other vehicles involved in a bicycle crash were motorised vehicles such as cars, buses or trucks (Orsi, Otte, Montomoli, & Mornadi, 2012). In addition, several other risk factors (other than the involvement of road users) were revealed by the analysis of these data sources, including intersections (especially roundabouts), specific cycling and driving manoeuvres (e.g. being overtaken, crossing, turning, speeding), environmental conditions (e.g. visual conditions), the state of the bicycle (e.g. no lighting, defective brakes), as well as specific rider and driver traits and states (e.g. age, intoxication; Boufous, de Rome, Senserrick, & Ivers, 2012; Candappa et al., 2012; Daniels, Nuyts, & Wets, 2006; Martínez-Ruiz et al., 2013; Orsi et al., 2014). However, it is well known that both overall crash statistics and in-depth investigations are biased towards incidents of higher severity (Elvik & Mysen, 1999; Tin Tin, Woodward, & Ameratunga, 2013); crashes with non-motorised vehicles are often not reported to the police, and hence do not appear in official statistics (OECD/International Transport Forum, 2012; Twisk & Reurings, 2013). In order to avoid the influence of such a bias, a new form of observational studies has been conducted in recent years: the so called *Naturalistic Cycling Studies (NCS;* Dozza & Werneke, 2014; Gustafsson & Archer, 2013; Johnson, Charlton, Oxley, & Newstead, 2010; Knowles, Aigner-Breuss, Strohmayer, & Orlet, 2012). An example is the work performed by Johnson et al. (2010), where daily work related cycling trips from commuters were recorded. A total of two collisions, six near-collisions and 46 critical incidents were classified, all of them involving another motorised road user. About 70% of the events occurred at an intersection or were noted as being intersection-related. Another Swedish NCS study presented similar results, finding that intersections and situations in which other road users crossed the path of the cyclist were major risk factors (Dozza & Werneke, 2014).

The term electric bicycle or e-bike may be used very liberally, such that two wheelers similar to scooters are labelled as e-bikes, especially in China. In Europe, the term electric bicycle or e-bike is mostly used to summarise all types of bicycles that provide electrical support. However, in some cases, the term e-bike is used to describe a specific type of the electric bicycle that allows the cyclist to ride without pedalling (Lawinger & Bastian, 2013; Otte, Facius, & Müller, 2014). In Germany, the term e-bike is usually applied to pedelecs and S-pedelecs [1]. Pedelecs (an acronym for pedal electric cycles) assist the rider whilst they are pedalling up to 25 km/h (250W). These are the most common type of e-bike sold in Germany, accounting for about 95% of all sales (Zweirad-Industrie-Verband, 2015b). Legally, they are considered equivalent to conventional bicycles, meaning that helmet use is not obligatory, and riders are allowed to use bicycle infrastructure. S-pedelecs provide motor assistance up to 45 km/h (500W) and are classified as powered two wheelers. For these, riders need a moped driving licence, motor liability insurance and also a helmet. They are prohibited to use bicycle infrastructure such as bike paths.

One central argument that e-bikes themselves increase risk has been voiced repeatedly: e-bikes can reach higher maximum speeds than conventional bicycles (Bai, Liu, Chen, Zhang, & Wang, 2013; Jellinek et al., 2013; Skorna et al., 2010). With increased use of e- bikes and pedelecs, the variance in speed amongst cyclists will increase, which might lead to a variety of problems (Boenke, 2013).

In recent years, several studies have investigated the average speed of e-bikes compared with conventional bicycles. Results from China (Cherry & He, 2009; Lin, He, Tan, & He, 2007) suggest that e-bikes are considerably faster than conventional bicycles. Mean speeds were found to be between 5 km/h (Cherry & He, 2009) and 7 km/h (Lin et al., 2007) higher. For users of a US bike share programme, higher average speeds were found for e-bikes (13 km/h) compared with bicycles (11 km/h) on conventional roads, whereas e-bike speed was lower on shared use facilities (Langford, Chen, & Cherry, 2015). Several European studies have examined the speed of electric bicycles. Two Swedish studies reported a mean speed of 14 km/h for bicycles (Dozza &

[1] In this dissertation, the term is used in accordance with this practice.

Werneke, 2014) and 17 km/h for e-bikes (Dozza, Piccinini, & Werneke, 2015), whilst both a Dutch study and an observational study in Germany found the average speed of e-bikes was about two to three km/h higher than that of conventional bicycles (Alrutz, 2012, 2013; Vlakveld et al., 2015). Prior to beginning this work, however, no data about speed were available in the literature separately for pedelec and S-pedelecs compared with conventional bicycles. Therefore, there is a need to examine the speed for the different bicycle types under various natural conditions, and this is covered here.

As a consequence of the higher speed of e-bikes, a rise in the number and severity of crashes is feared by some authors. Scaramuzza and Clausen (2010) estimated an increase of severe injuries of about 150%, and an increase of as much as 350% in fatalities if the overall cycling mean speed increases by 6 km/h. However, performing a risk assessment for electric bicycles is very difficult because, until now, limited crash data are hardly available. Initial statistics from China (Feng et al., 2010) suggest a high risk for e-bike users. Casualties and injury rates increased over a period of five years (2004-2008), even though the data were adjusted for the growth of the e-bike population. The main reason for e-bike related fatalities was speeding. When analysing the results of this work, caution must be taken, because the classification of e-bikes in China is not comparable to that in Europe; in China, scooter-like bikes are also classified as e-bikes. Therefore, the results could not be translated to the western hemisphere.

In Europe, only Switzerland has recorded e-bike crashes for a reasonable period of time (bfu-Beratungsstelle für Unfallverhütung, 2014). Since data collection began in 2011, a rise in the number of crashes with severe injuries and casualties has been seen. The sales figures of e-bikes increased simultaneously, which suggests a greater exposure of riders (bfu-Beratungsstelle für Unfallverhütung, 2013, 2014). For Germany, only crash data for the state of Baden-Württemberg are available so far, which shows the number of crashes also increased from 2010 to 2012 (Auto Club Europa, 2013). However, this data were not corrected to compensate for increased numbers of e-bike riders.

Up until now, it has been unclear whether crashes of e-bike riders were more severe than the ones involving cyclists, even though this presumption is often mentioned (Weber, Scaramuzza, & Schmitt, 2014). Otte et al. (2014) reported that, based on the comparison of bicycle and pedelec crashes, the severity of injuries of e-bike and bicycle riders did not differ. In contrast, a study in the Netherlands found out that the probability of e-bike users being involved in a crash that required hospital treatment was higher compared with conventional cyclists (Schepers, Fishman, den Hertog, Wolt, & Schwab, 2014). Also Scaramuzza, Uhr and Niemann (2015) affirmed that the severity of e-bike crashes is higher than for conventional cyclists, however it is confounded by age. It has already been mentioned that the age plays a role in crash severity of e-bike riders. Statistic data show that most of the e-bike riders who had a crash were 40 years and older (bfu-Beratungsstelle für Unfallverhütung, 2014; Weber et al., 2014).

In summary, cyclists are a high risk group in traffic. Research shows that most conflicts are with motorised vehicles, which results in a considerable number of severe injuries and fatalities. Single bicycle accidents and conflicts with other cyclists or pedestrians are often not taken into account, in particular because crash statistics are biased towards incidents with serious consequences. Hospital data show that it is also worth considering conflicts without motorised vehicles, since they are also a health issue and an economic burden (Veisten et al., 2007). Hence, this dissertation focuses on all conflict partners of cyclists. In addition, the effect of e-bikes on road safety is still unclear; the literature shows that e-bike riders travel faster than conventional cyclists. However, no data for different types of electric bicycles are available. This dissertation addresses this aspect by analysing the effects of different types of e-bikes on speed compared with conventional bicycles.

3.3.1 Drivers' gap acceptance and time to arrival estimations of approaching cyclists and e-bike riders

Until now, it is unclear how much of an impact the presence of e-bikes, which look very similar to conventional bicycles, has on the perception of other road users. Decision taken by a driver, such as overtaking a cyclist or an e-bike rider, depend on assumptions a driver makes about said rider (Walker, 2007). If an e-bike is perceived as a conventional bicycle by other road users, expectations about its speed may not be met; for instance, if the e-bike is suddenly much faster than expected, conflicts might follow in some circumstances (Bohle, 2015; Chaloupka-Risser et al., 2011; Skorna et al., 2010). An e-bike user described his experience in traffic in the following way: "I had to be really conscientious of other drivers because they weren't expecting me to approach as quickly as I was. And so, in the beginning, I feel like cars were kind of cutting me off because they thought they had plenty of time." (Popovich et al., 2014, p. 42).

In general, it is difficult for people to estimate speed correctly, be that their own or that of others. In experiments with explicit speed judgements, the subjects mostly underestimated the speed to a considerable degree (e.g. Barch, 1958; Evans, 1970; Triggs & Berenyi, 1982). At the same time, most road users seem to make implicit estimates of speed well enough to make decisions such as crossing the street or turning in front of an approaching vehicle. Previous research investigated these crossing or turning decisions with the paradigm of gap acceptance.

There is a long tradition of gap acceptance studies with car drivers (Blumenfeld & Weiss, 1979; Hurst et al., 1968). In these studies, mainly left turn decisions (right-hand traffic) were examined.

Due to the obvious potential danger in such situations, the experimental investigations were done on a test track, in a driving simulator, or with videos in a laboratory. Participants had to indicate when they would turn left into the traffic stream, by pressing a button or by means of a verbal statement. Afterwards, the accepted gap size was measured (e.g. Hancock, Caird, Shekhar, & Vercruyssen, 1991; Yan, Radwan, & Guo, 2007).

Studies that have used this methodology have shown that the speed of the oncoming vehicle has an influence on drivers' gap acceptance. It has been found that drivers accepted significantly smaller gaps as speed increased (Alexander, Barham, & Black, 2002; Bottom & Ashworth, 1978; Hancock et al., 1991). Yan et al. (2007) examined left turn decisions in a driving simulator and reported a gap of nearly 2 seconds smaller at 88 km/h than at 40 km/h. However, the accepted gaps did not result in collisions per se (Hancock et al., 1991). Drivers often made safe decisions, but all factors can contribute to a higher risk of unsafe decisions. In addition to speed, vehicle size was also reported to affect gap acceptance (Alexander et al., 2002; Bottom & Ashworth, 1978). In a study by Hancock et al. (1991), drivers turned left more frequently in front of an approaching motorcycle compared to a compact car or a delivery truck. If these results are transferred to other vehicles types, the smaller accepted gap size in presence of smaller vehicles leads to the assumption that cyclists might be at a higher risk compared to other vehicle types.

There is no doubt, however, that gap acceptance studies suffer from some methodological shortcomings. Often, the implementation of the gap acceptance situation lacks physical and / or functional fidelity (Hays, 1980). Physical fidelity, which refers to the level of realism of the environment that is employed (especially with regard to its visual quality), is often a problem in lab based studies that rely on artificial depictions of the traffic environment, such as driving simulations. The perception of depth is crucial to the estimation of the approach of a vehicle, a perception that is difficult to induce in artificial environments, which often lack multiple essential depth cues that are easily available in the real world (Alexander et al., 2002). Similarly problematic is the lack of functional fidelity, which describes the representation of authentic response options. The most valid way to investigate road users' gap acceptance would be to actually let them cross in front of an oncoming vehicle in real traffic. Instead, a lot of studies rely on button presses or verbal statements to indicate crossing intentions, an approach which, as te Velde, van der Kamp, Barela and Savelsbergh (2005) argued, neglects the automatic connection between perceived information and action. Other studies that actually require the participant to cross do so in simulator setups (Hancock et al., 1991; Yan et al., 2007), so that there are no realistic consequences, which also has the potential to distort the decisions that the participants make. A third issue is the problem of interdependence (Alexander et al., 2002). In real traffic, the behaviour of one individual will most likely affect the reactions of other road users. For example, even if a driver would select an unsafe gap for turning, other road users might compensate for such an error, and prevent a possible crash. This compensation is usually not reflected in experimental studies. Therefore, it is important to be clear that unsafe selected gaps in an experiment do not automatically translate into crashes in the real world. This shortcomings should be noted when interpreting the results of gap acceptance studies. However they are a safe and cost-effective alternative to studies in real traffic and in general make an important contribution to the investigation of crossing and turning crashes.

One factor that is considered to be vital for the decision making process of gap acceptance is the time to arrival (TTA, also named time to collision or time to contact), which means “the time remaining before something reaches a person or particular place” (Tresilian, 1995, p. 231). The estimation of the TTA is important for the evaluation of one’s own movement as well as of the movement of others. Previous research has particularly focused on the perception of the movement of other approaching vehicles (e.g. Caird & Hancock, 1994; Hancock & Manser, 1997). Two research methods have been established to evaluate the TTA: the relative judgement task and the prediction motion task. In the relative judgement task, the approaches of several objects or vehicles are compared directly (e.g. DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003; Seward, Ashmead, & Bodenheimer, 2007) whereas in the prediction motion task, an absolute prediction of when an object or vehicle would reach a certain point is made (e.g. Caird & Hancock, 1994; Schiff & Oldak, 1990). For the prediction motion task, short video sequences of an approaching vehicle are presented to the subjects. Before the vehicle reaches a specific point, the video sequences are paused. The subject then has to estimate when the vehicle will arrive at the specific point. As with gap acceptance studies, the answer can be provided by pressing a button or by giving a verbal statement. Pressing a button has been proven to have higher estimation accuracy (Schiff, Oldak, & Shah, 1992). Although tendencies to overestimate of the TTA have already been reported (Seward et al., 2007), a recurring finding while using this method is the underestimation of the TTA (Caird & Hancock, 1994; Hancock & Manser, 1997; Schiff & Oldak, 1990). This means that subjects expect the objects or vehicles to arrive sooner at a predefined position than they actually do, which leads to the assumption that subjects tend to overestimate the speed of an oncoming vehicle.

For TTA estimations, several influencing factors have been mentioned. As with gap acceptance, the speed of the approaching vehicle affected the TTA estimates. At higher speeds, longer TTA estimates were found (Petzoldt, 2014). With increasing speed, the estimates were more accurate, i.e. the underestimation was reduced (Manser, 1999; McLeod & Ross, 1983; Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996). However, this trend was not linear (McLeod & Ross, 1983).

Several studies have shown the “size-arrival effect” when assessing the TTA. Smaller objects or vehicles are judged to arrive later than larger ones (e.g. DeLucia & Warren, 1994; DeLucia, 1999; Horswill, Helman, Ardiles, & Wann, 2005). The accuracy of the TTA estimates decreased significantly from motorcycles to vans, i.e. subjects predicted that a delivery van would arrive earlier than a motorcycle when both were travelling at the same speed (Caird & Hancock, 1994). This finding is, again, particularly important for cyclists. Since bicycles and e-bikes are some of the smallest vehicles on the road, they could be affected by TTA overestimations by drivers of motorised vehicles who are turning, leading to crashes.

One issue with experiments studying TTA is that although the relationship of TTA estimates to actual behaviour in traffic, e.g. gap acceptance in crossing decisions, is implicitly assumed, it has been hardly ever established. Only Petzoldt (2014) at least tried to clarify the relationship between TTA estimates and accepted gap size in a lab study. Whilst his results showed that TTA estimation and gap acceptance can be closely related, evidence from a more realistic environment appears to be still missing. In general, as with experiments on gap acceptance, their lack of realism is one of the shortcomings of TTA experiments for the analysis of traffic safety issues (Manser & Hancock, 1996). Frequently, very simple visualisations of the traffic scenery, such as simulator like environments have been employed in studies investigating TTA judgements (e.g. Seward et al., 2007). Realistic video material captured in actual traffic might be considered a better approach (e.g. Horswill et al., 2005). However, in general it seems that the experimental setup in which TTA has been studied, regardless of the actual source of the material, has proven to produce valuable results over the years.

Summarising the findings above, it becomes apparent that for the majority of the gap acceptance situations and the TTA estimates drivers take safe decisions in general. However, for gap acceptances as well as for TTA judgements several factors affect these decisions. The characteristics of the oncoming vehicle, such as speed or size, influences estimations of the TTA and deciding when to turn. Additionally, the age of the car driver also had an influence on the TTA estimation and the gap acceptance.

As a review of the literature has shown, previous studies of both gap acceptance and TTA estimations focussed their analysis mainly on approaching cars (e.g. Hancock et al., 1991; Manser & Hancock, 1996; Recarte, Conchillo, & Nunes, 2005) or motorcycles (e.g. Gould, Poulter, Helman, & Wann, 2012; Horswill et al., 2005; Pai, 2011). As no studies of gap acceptances and TTA judgements of oncoming bicycles exist, this work aims to fill that gap.

3.4 Road user: Road safety of older road user

In 2050, nearly one third of the European population will be 65 years or older (Kubitzki & Janitzek, 2009), and it is expected that a considerable portion of this age group will be more mobile than the elderly today. This outlook has stimulated an increasing body of research on the mobility and safety of elderly road users. Given their increased mobility needs, the number of elderly riders is expected to grow in the years ahead. Therefore, one goal of this dissertation was to investigate the safety of older cyclists to provide some more scientific background to the ongoing discussion.

In the last 20 years, the number of crashes involving older road users has risen compared to the total number of crashes (Ortlepp, 2013). In absolute terms, although older road users have fewer crashes than younger road users, they also make fewer trips. When exposure is taken into consideration, older road users have a high risk of being involved in a crash. Statistics demonstrate that the most “at risk” are car drivers (representing about one half of the cases), followed by cyclists and pedestrians (Statistisches Bundesamt [Destatis], 2014b). Bicycles, and particularly e-bikes, are a popular mode of transport for older road users. Because of the ageing population, the number of such cyclists and e-bike riders is expected to increase. However, older cyclists are particularly at risk, as crash data (adjusted for exposure) shows. For riders 65 years and older compared to riders between 30 and 64 years, a greater number of crashes was reported (Martínez-Ruiz et al., 2014; Statistisches Bundesamt [Destatis], 2014b). Furthermore, the consequences of such crashes were more severe for riders in the older age range. Across a number of European countries, an increase in fatalities for older cyclists was found (e.g. Bíl, Bílová, & Müller, 2010; Ekman, Welander, Svanström, Schelp, & Santesson, 2001; Stone & Broughton, 2003). In Germany, figures from 2013 indicate that more than half of the cyclists killed in a crash were older than 65 (Statistisches Bundesamt [Destatis], 2014a). Thus, older cyclists are at a higher risk of death compared to younger ones (Oxley et al., 2004). Studies suggest that this is caused by the fact that the elderly are more vulnerable than younger individuals, because of a decrease in the physiological strength and resistance (Bíl et al., 2010; Ekman et al., 2001). They were also more prone to being severely injured when a crash occurred (Boufous et al., 2012; Oxley et al., 2004). Scheiman, Moghaddas, Björnstig, Bylund and Saveman (2010) found that older cyclists had a much higher rate of severe injuries, such as fractures or intracranial injuries, compared to younger riders. Additionally, they also required longer periods of treatment and needed more time for recovery.

Crashes involving older road users have particular characteristics. An investigation of drivers revealed that crashes happened whilst they were performing a turn manoeuvre or made a misjudgement about right of way (Ortlepp, 2013; Statistisches Bundesamt [Destatis], 2014b). This might be explained by the changes in physical and cognitive processes due to ageing. Oxley et al. (2004) stated that “There is general agreement that ‘normal’ ageing reduces or slows down sensation, perception, cognition, psychomotor response and physical functioning and all of these composites have a logical relationship to driving, walking and cycling.” (p.32). Physical impairments that affect the vision, such as presbyopia - a decrease of field of view, in visual acuity or peripheral vision – were highly relevant (Hagemeister & Tegen-Klebingat, 2012; Hagenzieker, 1996; Ortlepp, 2013). Additionally, the reduced agility of older people can cause problems because motor responses take longer and their strength is diminished. As these functions are very important for cycling, their decrease might cause instability and lead to crashes. This could be the reason why elderly riders often suffer in single bicycle accidents (Davidse et al., 2014; Scheiman et al., 2010). In addition, a limited ability to turn one’s head can be problematic, both for drivers and cyclists, at intersections or whilst performing parking manoeuvres (Oxley et al., 2004; Schlag & Weller, 2013). Thus, all these physical limitations can contribute to the higher crash risk of older people.

It is not only physical concerns which are important when considering the risks for elderly riders. Cognitive, sensational and perceptual skills are also essential for safe cycling. Vlakveld et al. (2015) reported longer reaction times for older compared to younger cyclists in both simple and complex traffic situations. Elderly people were also shown to have a higher mental workload (Boele-Vos, Commandeur, & Twisk, 2015). Other studies showed that the selective attention and the distance perception of older road users might be reduced (Hagenzieker, 1996; Ortlepp, 2013; Schlag & Weller, 2013), causing problems with the estimation of distance and speed; this could lead to bad decisions during road crossings (Oxley, Ihsen, Fildes, Charlton, & Day, 2005; Oxley, Ihsen, Fildes, & Charlton, 2002).

The current findings about older road users indicate that they are a high risk group in road traffic. The fatality and injury rate are much higher than they are for their younger counterparts. This might be explained by the reduced cognitive and physical abilities through the normal ageing process. It has been found that for older cyclists and e-bike riders, the risk of severe injuries or death is effectively doubled.

3.5 Infrastructure: Influence of infrastructure and its characteristics on road safety

Several attributes of the infrastructure are important influences on the safety of cyclists, such as the type of infrastructure, the existence of intersections and the gradient. A specific characteristic of cyclists is that they use many different types of infrastructure, including roads (shared with motorised vehicles), bicycle-specific infrastructure, and pavements (which are primarily for pedestrians). Additionally, bicycle-specific infrastructure is very diverse and includes different types of bicycle lanes, bike paths or separated bicycle paths. Bicycle lanes may be part of the road itself, marked out by a coloured surface or painted lines (see Reynolds, Harris, Teschke, Cripton, & Winters, 2009). Other bicycle paths are paved lanes next to the road, but segregated by a curb or other physical barriers. Sometimes, they are shared with pedestrians. Some bicycle paths or cycle tracks are entirely separate without any direct link to a road. They may be paved or unpaved. A survey about perceived risks for cyclists revealed that separate bicycle paths were perceived being safer than bike lanes, roads or pavements (Lantz, 2011). Caulfield, Brick and McCarthy (2012) showed that cyclists preferred segregated or separate bicycle paths, whereas they were less likely to choose a route on a “cycle/bus lane” or on the road itself due to safety issues. Similar results were reported in a study which analysed GPS data from cyclists and investigated their route choices (Broach, Dill, & Gliebe, 2012). Here, separated bicycle paths were also the most preferred type of facility. In addition, the authors also found that designated bicycle infrastructure in general was preferred to low traffic streets, local streets or high traffic streets.

It seems that the observed choices of cyclists are justified by statistics. According to accident statistics, bicycle crashes occurred more often on the road than on bicycle infrastructure (OECD/International Transport Forum, 2012). Also hospital data from Germany showed that about 70% of the crashes happened on the road compared to nearly one fifth on bicycle infrastructure. Where accidents do happen on bicycle infrastructure, the reported injuries are also less severe (Richter et al., 2007). Reynolds, Harris, Teschke, Cripton and Winters (2009) summarised ten relevant studies in a review and investigated the safety of different infrastructure types. In comparison to the road itself, a reduced risk of crashes was found for different types of bicycle infrastructure, such as bicycle lanes or bike paths, although riding on pavements enhanced the crash risk compared to riding on the road. An Australian study (De Rome et al., 2014) also found that cycle lanes had a reduced crash risk and - in contrast to the findings of Reynolds et al. (2009) – so did pavements.

The risk of injury was investigated for several infrastructure types by Teschke et al. (2012), using hospital data. The highest injury risk was reported for major streets with high traffic volume and parked cars. A reduction in risk was observed for bicycle lanes, and the reduction was even greater for separate bicycle paths. Local streets with low traffic were also found to have a significantly reduced risk of injury. Even though Reynolds et al. (2009), found that risk of crashes on pavements was high, Teschke et al. (2012) discovered a small risk reduction for injuries on pavements. Most of these results could be confirmed by a subsequent study (Cripton et al., 2015). However, in this work, the injury risk for specific bicycle infrastructure was the same as for major streets. The authors explained this result by noting that the bicycle lanes considered were not segregated from motor vehicle lanes, whereas in the previous studies separate bicycle paths were analysed.

Intersections provide a particular risk of crashes and serious injuries (e.g. Dozza & Werneke, 2014; Walker, 2011). Up to half of the fatal crashes occurred at intersections, and a similarly high percentage of the crashes with injuries were related to them (OECD/International Transport Forum, 2012). Also in naturalistic cycling studies (NCS) the majority of safety critical events were noticed at intersections, particularly the ones without any form of traffic control (Dozza & Werneke, 2014; Johnson et al., 2010). Most of the crashes with severe injuries at intersections involved cars, which often failed to correctly yield right of way to the cyclist (Walker, 2011). A special form of intersections are roundabouts. Daniels et al. (2006) showed that cycling crashes increased by a third after intersections were transformed into roundabouts. Moreover, severe or fatal crashes increased by about 50% and as much as 80% in urban areas. Other studies have also found an increase in injury risk for roundabouts and intersections of major streets (Harris et al., 2013; Reynolds et al., 2009).

The road gradient has also been seen to have an influence on cycling safety. Downhill riding is usually accompanied by higher speeds (Llorca, Garcia, & Torres, 2015), limiting the possibility of a timely reaction and extending the braking distance. This might be an explanation for the significant increase in injury risk rate on downhill gradients compared with flat or uphill gradients found by Harris et al. (2013). In addition, the injury severity has already been reported to be higher for these situations (Cripton et al., 2015; Teschke et al., 2012) and an increase of severity was found for both curved and straight downhill grades (Klop & Khattak, 1999).

In conclusion, based on hospital data and crash statistics, bicycles infrastructure seems to improve the safety of cyclists, whereas riding on roads themselves (particularly with high traffic density) leads to more crashes and higher injury severity. Also, intersections pose a higher risk for cyclists.

4 Research objectives of the dissertation

Against a background of current knowledge, the different components of this dissertation addressed the question of whether bicycle type, the age of the rider or characteristics of the infrastructure might have implications for bicycle safety. To answer this general question, the following research objectives were specified:

1. As reported previously, earlier researcher assumed that e-bike riders travel at higher speeds than conventional cyclists. Differences between several types of e-bikes were expected. However, at the beginning of this dissertation project, no European data concerning the speed of e-bikes compared with conventional bicycles were available to support this claim, neither generally nor more specifically for different types of e-bikes (pedelec, S-pedelecs). Therefore, as a first objective, in Paper I it was examined, if there are differences in speed under various conditions for three different bicycle types (conventional bicycles, pedelecs, S-pedelecs).
2. As reported above, other road users have to judge the speed of an approaching bicycle when making decisions to turn or cross the road. Since car drivers have less experience with e-bikes and their potential to reach higher speed, a misjudgement of their speed respectively their approach and therefore inadequate crossing decisions could be made. Previous research investigated the decision making process with the help of studies on gap acceptance or TTA estimations. The second objective was therefore to examine how drivers' gap acceptance or time to arrival estimates are influenced by speed and type of bicycle. This was addressed in Paper III and Paper IV.
3. Special consideration was given to the age of the cyclists as an influencing factor on road safety. Elderly people, as a main user group of e-bikes and bicycles, play a particularly important role. Functional limitations as a result of the ageing process are potentially problematic for the control of the bicycle, especially with the potentially higher speed of an e-bike. The third research objective was to investigate whether there are speed differences between older, middle aged and younger riders of conventional cyclists and pedelecs - and, if so, to what extent. This was considered in Paper I.
4. The potential speed differences between the age groups could mean that some age groups are more prone to crashes than others. Thus, the fourth objective was to study how the age of the rider influences the frequency of crashes and safety critical events under several conditions. This was undertaken in Paper II. The analysis presented in this paper looked specifically into the circumstances under which safety critical events occur (e.g., other road users, time of day), and how these events can be described.

5. As mentioned previously, the infrastructure is an important pillar of traffic safety. The infrastructure on which a cyclist is travelling on can have a considerable influence on his cycling speed, and also on the cyclist's probability to crash. The gradient in particular can influence speed, which might lead to safety problems. The fifth objective was to examine if or how different types of infrastructure influence the speed and occurrence of safety critical events (Paper I and Paper II). More specifically, the question was, if cyclists and e-bike riders travel faster on roads than on other types of infrastructure and if a higher speed is accompanied by an increased number of safety critical events. In addition, it was investigated how the road gradient influences the speed of the rider and the perception of this speed by other road users (Paper I and Paper III).

5 Overview of the methodology

Two earlier projects form the basis of this dissertation: Pedelec-Naturalistic Cycling Study (P-NCS) (Schleinitz et al., 2014) and Speed perception of two wheelers (Schleinitz, Petzoldt, Krems, Kühn, & Gehlert, 2015), which were both funded by the German Insurers Accident Research.

The relevant variables for the different research questions were gathered using different methods. As a first step, the P-NCS was conducted to examine the similarities and differences in cycling safety behaviour of cyclists and e-bike riders. This gave rise to new research questions concerning the behaviour of other road users who interact with conventional cyclists and pedelec riders. Thus the second step was to conduct experimental studies under controlled conditions to verify how other road users make decisions when cyclists are present. In Papers I and II, the methodology for the P-NCS is explained in detail, whereas in Papers III and IV the controlled experimental studies were presented. In the following sections, the method of the P-NCS and the experiments will be summarised.

5.1 Naturalistic Cycling Study

In the last decade, a new approach of studying human behaviour and interaction with motorised vehicles, known as naturalistic driving studies (NDS) was developed. Until now, most such studies have been conducted with cars and trucks (Dingus et al., 2006; Eenink, Barnard, Baumann, Augros, & Utesch, 2014; Hallmark et al., 2013; Lehmer et al., 2012; Victor et al., 2014). In NDS, vehicles used by the participants are equipped with a data acquisition system (DAS) which usually consists of cameras, sensors, and a data storage unit to capture driving behaviour under real-world conditions. This allows the driver behaviour and all important events to be recorded without the need for a human observer to be present. These studies are typically performed to investigate crashes, near crashes or critical incidents, as well as the relevant behaviours and environmental conditions. A small number of naturalistic cycling studies (NCS), which are based on the NDS, have been conducted in recent years (e.g. Johnson et al., 2010; Knowles et al., 2012). As with NDS, NCS provide a strong external validity (Boyle et al., 2012; Werneke, Dozza, & Karlsson, 2015) and allow for the detailed analysis of crashes, as well as near crashes and minor incidents which are missing in accident data (Johnson et al., 2010). It is possible to paint a complete picture of cycling behaviour. However, the prize for this high external validity is a lack of experimental control. Also, so far, the generalisability of most investigations is rather limited, as they usually were conducted with only a small number of participants in one city for a specific time of the year (Dozza & Werneke, 2014; Johnson et al., 2010). The potential self-selection of participants, who are mostly highly committed individuals, adds to this problem (Dozza & Werneke, 2014). Because of the large amount of data, in particular video data, the process of data analysis is very complex, expensive and time consuming (Gustafsson & Archer, 2013). In addition, the fact that there often is a great variance in the number of trips collected for the different participants (Werneke et al., 2015), and that some of routes and areas might be overrepresented in the data (Johnson et al., 2010) creates a considerably challenge for data analysis. Still, despite these potential issues, NCS are, to date, the best method for the investigation of cyclists' behaviour, especially their speed choice and their involvement in safety critical events, as only NCS allow for the collection of actual real world behavioural data.

For this study the DAS used was similar to that which was used in previous NCS (e.g. Gustafsson & Archer, 2013; Johnson et al., 2010). The components of the DAS and its functions are explained in the methodology sections of Papers I and II. Questionnaires and a travel diary were also used in order to collect data about the mobility behaviour of the participants, such their cycling habits and their reasons for making a trip. A detailed description of the surveys and the travel diary from the P-NCS can be found in Gehlert et al. (2012). The data collected in the surveys and travel diaries are not part of this dissertation project. An overview of the procedures of the P-NCS is illustrated in Figure 1. The study was carried out in and around Chemnitz (Germany) between July and November 2012. Data were recorded over a period of four weeks for each participant. The participants were recruited through advertisements in newspapers or flyers in bicycle shops. The prospective participants completed a recruitment questionnaire (including contact information, and technical data about their bicycle). Age and bicycle type were used as criteria for selecting participants. Ninety riders (31 conventional cyclists, 49 pedelec riders, 10 S-pedelec riders) were chosen for participation. The participants were grouped by age as follows: younger participants (40 years and younger), middle aged participants (41-64 years) and older participants (65 years and older). For each participant, an individual appointment for the fitment of the DAS to their bicycle was arranged. A technician mounted the DAS on each participant's bicycle, and conducted a short cycling skill test with the participants in order to check their level of ability. During this process, participants completed the preliminary survey. The participants were asked to keep a travel diary for a period of one week during the observation period, although this was not analysed for this dissertation project. Necessary maintenance procedures (such DAS repairs or the exchange of storage media) were carried out by trained technicians. After four weeks, the DAS was removed and participants filled in the post-observation survey. Overall, about 4,300 trips with a total distance of nearly 17,000 kilometres were recorded during the four weeks of data collection.

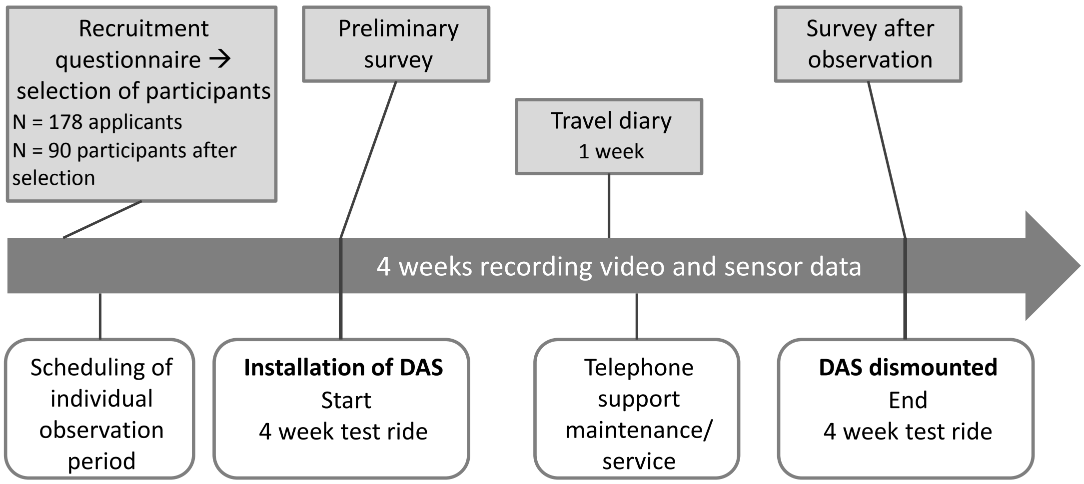

Figure 1. Study procedure of the P-NCS.

5.2 Experimental studies

Studies which examine the gap size which drivers accept to turn left (across traffic) have been conducted for some years. Early studies were conducted on test tracks or in real traffic (Bottom & Ashworth, 1978; Gibbs, 1968; Hurst et al., 1968), but – as technology improved - later experiments were conducted in driving simulators, because of the reduced safety risks, lower costs and reduced implementation efforts (Alexander et al., 2002; Hancock et al., 1991).

In order to investigate the accepted gap size under conditions which were as realistic as possible, the experiment presented in Paper III was conducted on a test track. Participants were invited to sit inside a real car and observe an approaching cyclist. They were asked to depress a foot pedal when the cyclist reached a point corresponding to the minimum acceptable gap for turning left in front of the cyclist. The participants did not have to actually turn left in the study. The detailed methodology is described in Paper III.

Experiments concerning time to arrival (TTA) estimates have rarely been conducted as test track experiments (Recarte et al., 2005); most such experiments use short video sequences presented on a screen in a laboratory (Herstein & Walker, 1993; Horswill et al., 2005; Marmeleira, Ferreira, Godinho, & Fernandes, 2007; Scialfa, Lyman, Kline, & Kosnik, 1987). In the two experiments presented in Paper IV of this dissertation, a similar video based laboratory study was implemented, with the aim of gathering TTA estimates of the participants for a conventional bicycle and an e-bike with different speeds.

6 Results and discussion

The following chapter provides a short overview and discussion of the results given in the dissertation. A broader discussion with all the details is presented in Papers I to IV.

6.1 Vehicle: Traffic safety of bicycle and e-bike riders

This section describes the results of the effects (in relation to conventional bicycles) on the speed of the riders, and the speed perception through other road users of pedelecs (which provide assistance up to 25 km/h) and S-pedelecs (which provide assistance up to 45 km/h).

6.1.1 Research Objective 1: Influence of bicycle type on speed under various conditions

In Paper I, the influence on speed in comparison to conventional bicycles of the two types of electric bicycles were investigated. The analysis revealed significant differences between the three bicycle types. In general, S-pedelec riders were the fastest. The speed was, on average 7 km/h higher than for pedelecs, and 9 km/h higher than for conventional bicycles. Under free-flow conditions (without curves or other obstacles, and with no other road users in front of the cyclist), the speed was generally slightly higher than the regular mean speed, but, again, the S-pedelec riders were the fastest group. Additionally, they covered a much larger portion of their total travelling distance at higher speeds. More than 80% of their total riding distance was covered at a speed of 20 km/h or above, and 34% of their riding distance was covered at a speed of 30 km/h or higher.

S-pedelecs are rather rare, and no study to date has investigated their speed. Hence, making comparisons with previous findings is difficult. However, in studies from Cherry and He (2009) and Lin et al. (2007) the types of e-bikes considered were very similar to S-pedelecs. These studies also found higher speeds similar to the results reported in Paper I.

This work showed that, for pedelecs a significant higher average speed was found than for conventional bicycles in all conditions including under free-flow conditions. Pedelec riders covered a significantly higher portion of their total distance at a speed 20 km/h or higher than cyclists did. However, there was no difference in the proportion of distance covered at 30 km/h or more. These results are in line with findings from other studies which compared the speed of pedelecs with conventional bicycles (Jellinek et al., 2013; Onnen-Weber, Schramek, & Butz, 2012; Vlakveld et al., 2015).

In summary, these findings indicate that e-bike riders, and in particular S-pedelec riders, use the support that the motor assistance provides to ride faster. Some authors argue, that a higher speed is accompanied with a higher crash risk (Aarts & van Schagen, 2006; Elvik, Christensen, & Amundsen, 2004). Therefore, it can be assumed that riders of e-bikes have a higher risk of being involved in a crash than riders of conventional bicycles. Furthermore, higher cycling speeds have already been associated with a greater risk of severe or fatal injuries (Rivara, Thompson, & Thompson, 1997). Therefore, higher travelling speeds might be one factor contributing to higher risk for e-bike riders when compared to conventional cyclists. Even if riding an e-bike does not necessarily imply a higher number of crashes, the crashes that occur result in a greater number of hospital admissions (Schepers, Fishman, et al., 2014).

6.1.2 Research Objective 2: Effect of speed and bicycles type on drivers' gap acceptance and time to arrival estimates

Based on the results of Paper I, which found that both types of e-bikes have higher mean speeds than conventional bicycles, it seemed pertinent to examine how the speed and the bicycle type affect the speed perception of other road users. Drivers are of particular interest here, since most of the bicycle crashes involved motorised vehicles. Theoretically, the bicycle type should have no influence, since conventional bicycles and e-bikes look similar. However, previous studies of e-bike riders showed that their speed might be underestimated by other road users (bfu-Beratungsstelle für Unfallverhütung, 2014; Jellinek et al., 2013; Popovich et al., 2014). For this reason, this work took a closer look at this problem.

Two measures for speed perception were used: gap acceptance and TTA estimates. In Paper III, the effect of speed and the bicycle type on the gap acceptance was studied. In Paper IV, the influence of these factors on TTA estimates of drivers was observed.

As with previous studies (Alexander et al., 2002), the test track experiment found that drivers chose significantly smaller gaps when the approach speed of the riders was higher. Although the vast majority of accepted gaps would still have allowed the critical manoeuvre to be performed safely (without the occurrence of a crash), the critical gap size was too small in 2.5% of the cases - which means that a crash would have occurred, if the rider would not slow down. Speed had also an effect on TTA estimates, which rose significantly with higher speed. This supports the results of previous studies (e.g. Manser, 1999; Sidaway et al., 1996) and underlines the argument that e-bike riders, with their potential to reach higher speeds, might be at increased risk.

When the types of bicycles were compared, it was found that drivers accepted significantly smaller gaps in front of an electric bicycle than in front of a conventional bicycle. When interpreting these results, it should be taken into account that drivers had no prior knowledge about the different types of bicycles used, which means that they should consider both bicycles as conventional bicycles. The two bicycles looked nearly identical, such that the effect of bicycle type could not be down to the distinct appearance of the bikes. In addition, similar findings for TTA estimates were also verified by Experiment I. Similarly, a significant effect of bicycle type on TTA estimates was found; the e-bike was judged as arriving later than the conventional bicycle at the same speed. This effect cannot be explained by the size arrival effect, because the bicycles are identical in size and shape.

Likewise, in the video study it was impossible for the participants to differentiate between the e-bike and bicycle. Consequently, these results support the findings of gap acceptances and the statements of the e-bike riders. It is apparent that drivers underestimate the speed of an approaching e-bike. One possible explanation for the effects is the perception of the driver about the rider and not of the bicycle. Humans are unconsciously trained to perceive the biological motion of others (e.g. Johansson, 1973; Vanrie & Verfaillie, 2004). Hemeren et al. (2014) found that participants were able to predict the intention of a cyclist to cross a street by their motion. Therefore, it seems possible that potential differences in posture and pedalling frequency when using an e-bike compared to a conventional bicycle were used as indicators. Due to the pedalling support of an e-bike, the rider’s effort and pedalling frequency is lower than when riding a conventional bicycle travelling at the same speed. The reduced effort might also be reflected in the cyclist’s position on the bicycle. This overall picture might be interpreted by another road user as a rider approaching slowly.

Following findings of the first experiment concerning TTA estimates, the effect of pedalling frequency - in addition to speed and bicycle type - was tested in a second experiment. As in Experiment I, results showed that speed had a significant effect on TTA estimates. An effect of bicycle type on TTA estimates could not be seen, but pedalling frequency was revealed to have a significant influence. A cyclist approaching with a higher pedalling frequency was judged to arrive earlier than one with a lower frequency. Moreover, the effect of pedalling frequency was independent of bicycle type, i.e., for both the e-bike and the conventional bicycle, higher pedalling frequencies corresponded to shorter TTA estimates. Thus, the results underline the relevance of the cyclist's motion pattern for TTA estimation.

In conclusion, the findings for Research Objective 1 support the assumption that S-pedelec and pedelec riders travel with higher speed than conventional cyclists. This alone might be a risk factor for an increased frequency and severity of crashes. Additionally, the experimental work here has shown that drivers misjudge the speed of an approaching e-bike. E-bikes were judged as arriving later than conventional bicycles, and drivers accepted smaller gaps in front of e-bikes. This effect is mainly driven by a perceived reduction in effort of the cyclist due to a reduced pedalling frequency. However, the higher speed of e-bikes together with the underestimation of their approaching speed by drivers could lead to riskier crossing and turning decisions and therefore enhance the risk of collision with e-bike riders. Crash statistics from China support this assumption. The number of e-bike related injuries and fatalities increased in recent years, whilst the number for overall road traffic and conventional bicycles decreased (Feng et al., 2010; Zhang, Cui, Gu, Stallones, & Xiang, 2013). For Europe, no clear picture can be drawn, since reliable data are only provided from Switzerland, where the number of crashes was seen to increase, but there was no correction for exposure (bfu-Beratungsstelle für Unfallverhütung, 2014). Otte et al. (2014) found a higher percentage of crashes in which other road users entered or crossed the path of the rider for pedelec users compared with conventional cyclists. Only time will tell how the number of crashes involving e-bikes will change; however, the present findings suggest that the underestimation of the higher speed could be a risk factor, especially for S-pedelecs. This should be considered in any discussion of road regulations and other related measures (see Chapter 8).

6.2 Road user: Traffic safety of bicycle and e-bike older riders

The findings of Research Objectives 3 and 4 reflect the influence of age of cyclists and e-bike riders on speed and traffic safety (especially for older riders). Specifically, the difference between three age groups are highlighted and discussed.

6.2.1 Research Objective 3: Influence of age on speed of riders of bicycles and pedelecs.

In Paper I, the influence of three age groups (40 years and younger, 41-64 years, 65 years and older) on speed was examined (in addition to the effect of bicycle type). The younger participants were the fastest overall, whereas the older ones rode significantly slower, even under free-flow conditions. Compared with both younger groups, the oldest group of riders travelled the shortest distances at higher speeds. These findings were consistent with the results of other studies (Jellinek et al., 2013; Lin et al., 2007). In addition, the effect for older riders did not depend on the bicycle type. Jellinek et al. (2013) found that the mean speed was 3 km/h lower for cyclists as well as for e-bike riders aged 65 years and older compared with younger riders (aged 25-64 years).

The age effect persisted under specific conditions as well. The older riders were the slowest whilst riding uphill and downhill, whereas the youngest group produced the highest speed. This effect cannot be explained solely by physical strength, especially for downhill riding. Therefore, the reduced physical strength of the older riders does not seem to be the only reason for slower cycling. This assumption is also supported by the fact that the age effect exists independently of bicycle type. One possible explanation for this findings is that older riders travel more carefully than the younger riders, potentially in order to prevent falls (which are more common for elderly; Scheiman et al., 2010). It may be that they fear that severe injuries are associated with a longer period of treatment in hospital or even with a permanent loss of mobility.

An interesting finding was the fact that older pedelec riders were on average slower than the younger and middle aged riders of conventional bicycles. Therefore, it cannot be assumed that all e-bike riders were faster than cyclists. It would appear that the older riders used the motor assistance of the pedelec to ride with less effort instead of riding faster. Additionally, the assumption that older riders of pedelecs in particular travel at speeds beyond their control is mostly not supported. It seems that they compensate for their reduced functions due normal ageing by riding slower. Of course, individual cases and situations in which control is lost due to excessive speed might still occur, but they also do for younger cyclists.

6.2.2 Research Objective 4: Influence of age on safety critical events and crashes of cyclists

Paper II focuses on the differences between age groups regarding safety critical events (SCEs) only for conventional cyclists. For this purpose, the video data of the P-NCS were annotated in order to identify safety critical events and to describe their circumstances. For a total of 400 hours of cycling, 77 safety critical events were found. Nearly one third of the participants were not involved in any SCE. More than the half of the participants experienced one to three events and only six cyclists were involved in four or more SCEs. In order to assess the potential effect of age on the occurrence of SCEs, the amount of exposure (distance travelled) was compared to the relative frequency of SCEs for each age group (the Safety Incidence Rate (SIR) was defined as the number of SCEs per 100 km travelled; OECD/International Transport Forum, 2013). No differences concerning the relative frequency of SCEs and related to exposure (SIR) were revealed between the three age groups, which indicates that older cyclists are not more at risk than younger cyclists.

For all age groups, the majority of the events occurred in the afternoon (between 14:00 and 16:59), the time when the cycling activity was highest. Thus, after correction for exposure, the risk of an SCE appears to be highest in the afternoon hours. Another peak was found for the younger and older cyclist groups in the morning (between 8:00 and 10:59). At these times, since many commuters are on the road, high traffic density may be assumed, resulting in a higher collision risk.

A more or less identical pattern for all age groups was found for the conflict partners involved in the SCEs. The most frequent conflict partners were cars, followed by pedestrians and other cyclists. However, even though cars were still the most frequent conflict partner, the proportion of SCEs involving motorised vehicles was only slightly above 40%, while SCEs with non-motorised road users (pedestrians and other cyclists) accounted for nearly 60% of all incidents. This was also found in a Swedish NCS where only one third of the SCEs occurred with motorised vehicles, and pedestrians and cyclists were the most frequent collision partners (Dozza & Werneke, 2014). However, these results show a clear difference with data from crash statistics, where cars account for nearly three quarter of crashes (Statistisches Bundesamt [Destatis], 2014a). This underlines the assumption that crashes with a higher severity, such as those caused by motorised vehicles, were more often recorded in crash statistics than crashes with minor injuries, (including those involving a collision with other cyclists or pedestrians; Juhra et al., 2012). Also single bicycle accidents were not reported in crash statistics, even though they are not negligible (e.g. de Geus et al., 2012; Tin Tin, Woodward, & Ameratunga, 2010). Older cyclists in particular were often involved in single accidents (e.g. Boele et al., 2015; Davidse et al., 2014). Therefore, this provides further evidence that an investigation of crashes involving older road users should not be limited to crash statistics.

In general, when considering the influence of road users on road safety, it can be seen that older riders did not experience more safety critical events than the younger ones, probably because of their slower speed. This aspect might be considered as a compensation for the sensual, perceptual and physical impairments through ageing. However, even when the number of crashes or safety critical events was not higher compared to younger riders, there is evidences in the literature to suggest that the consequences of a crash could be more severe for older cyclists and e-bike riders (Boufous et al., 2012; Rodgers, 1997). Kaplan, Vavatsoulas and Prato (2014) stated that compared to younger people, cyclists over 60 years old are at much greater risk of sustaining severe injuries.

6.3 Infrastructure: Influence of infrastructure circumstances on traffic safety

6.3.1 Research Objective 5: Infrastructure type and road gradient as influencing factors on speed and speed perception of cyclists and e-bike riders and their effect on safety critical events

In Paper I, the influence of various infrastructure characteristics, including infrastructure type and road gradient, was also assessed. The speed of the riders was affected by the road gradient. When riding downhill, the participants were nearly 6 km/h faster than when cycling uphill. This might be one explanation for the higher number and greater severity of crashes when cyclists rode downhill than uphill or on flat roads (Cripton et al., 2015; Harris et al., 2013). The influence of road gradient was the same for all bicycle types and age groups. The effect of the road gradient was also examined in the test track experiment (Paper III). The drivers observed an approaching cyclist riding uphill and on a road with no grade. When the approaching cyclist was riding uphill, accepted gaps were smaller then when there was no grade. This effect was also independent of bicycle type. It was found that different aspects of riding uphill and downhill could have a negative impact on traffic safety. It can be assumed that cyclists and e-bike riders were at a higher risk of crashes caused by car drivers turning or crossing when riding uphill, because drivers misjudge the approach speed, whereas when riding downhill the high speed of the rider itself has consequences which could be safety critical.

When considering infrastructure type, the highest speed was found on roads and on bicycle infrastructure (Paper I). The slowest speed was recorded for miscellaneous types of infrastructure (which included small paths between houses/in allotments or parking facilities). Riders travelled relatively fast on pedestrian infrastructure, such as pavements and pedestrian precincts, and similar speeds were measured for unpaved roads. It has to be noted that there was a lot of illegal infrastructure use. In Germany, riding on pavements or pedestrian precincts is generally forbidden, with only a few exceptions for cyclists and e-bike riders. Cyclists nonetheless travelled relatively fast on these infrastructure types, although their mean speed still suggests that they adapt and slow down compared with riding on bicycle infrastructure or the road itself.

S-pedelec riders were the fastest on all infrastructure types. Their high speed on bicycle infrastructure was particularly striking, especially when compared to the other two bicycle types. The use of S-pedelecs on bicycle infrastructure is illegal, yet the participants nonetheless covered about one sixth of their total mileage on it. The speed of pedelecs and conventional bicycles differed only on bicycle infrastructure or the road itself, whereas it was nearly the same on other infrastructure types. This suggests that the potential of pedelecs can be especially exploited under free-flow conditions, which are hardly found on infrastructure types other than roads or bike paths.

In Paper II, the results about the SCEs for various infrastructure types were reported. In order to assess the potential risk (SIR) for conventional cyclists on different types of infrastructure, the amount of exposure to different infrastructure types was compared to the relative frequency of SCEs across different types of infrastructure. When investigating SCEs across different types of infrastructure, it was obvious that riding on the road itself was relatively safe. Even though more than half of the total trip distance was covered on road, only about one third of the SCEs happened there. It has to be noted that in travel diaries reported in other studies (de Geus et al., 2012) and in data collected at crash scenes (Richter et al., 2007), the proportion of crashes that occurred on the road was close to 70%. However, exposure was not controlled in the studies, so it remains unclear how the relatively high number of crashes on the road relates to actual risk. Still, the fact that the conflict partner in incidents on the road was most often a motorised vehicle implies that the consequences of an on road crash would also be more severe (Kaplan et al., 2014; Walter, Achermann Stürmer, Scaramuzza, Niemann, & Cavegn, 2012).

In contrast to the road, the risk of SCEs on bicycle infrastructure per distance travelled was relatively high. One third of all SCEs were observed there, although this type of infrastructure was used for only a quarter of the total distance travelled. This finding is contrary to the reports of Reynolds et al. (2009) and De Rome et al. (2014), who found a reduced safety risk on bicycle infrastructure. However, their results were based on self-reports or crash data, which are biased towards more severe crashes (e.g. Elvik & Mysen, 1999). In general, it appears that it is relatively safe to cycle on unpaved roads and paths, which might be explained by the fact that cyclists seldom encounter other road users on that infrastructure type. For miscellaneous infrastructure (such as parking facilities), the SIR was relatively high. This is presumably because no (clear) rules and regulations are usually provided for such types of infrastructure, which might enhance the complexity of the situation. In line with the findings of speed on this infrastructure type, these SCEs were low speed events.

In conclusion, the highest speeds were measured on bicycle infrastructure and on the road itself. However, travelling on the road was relatively safe compared to using bicycle infrastructure when relative exposure was taken in to account. Speed is unlikely to be the only reason for this difference, since the mean speed was very similar for both infrastructure types. However, cyclists perceived bicycle infrastructure as safer than the road (Caulfield et al., 2012; Lantz, 2011). This raises the question of whether cyclists misjudge the risk, but they do not necessarily because different types of crashes occur on bicycle infrastructure than on roads. The results in

Paper II suggest that on bicycle infrastructure, conflicts with pedestrians or other cyclists (mainly crossing conflicts with pedestrians or sudden swerving and braking by other cyclists) were more likely than with motorised vehicles, whereas on roads it was reverse. The ambiguous distinction between the bicycle infrastructure and pavement may lead to these conflicts. Pedestrians frequently used bicycle infrastructure, which caused problems.

An explanation for cyclist-cyclist conflicts on bicycle infrastructure might be the comparatively poor knowledge cyclists have about the rules, especially with regard to this type of infrastructure (Huemer & Eckardt-Lieberam, 2015; Huemer, Eckardt-Lieberam, & Vollrath, 2014), coupled with a considerable lack of compliance. For instance, observational data suggest that up to 20% of cyclists use the bicycle infrastructure in the wrong direction (Alrutz et al., 2009). Naturally, this can cause problems with cyclists riding in the opposing (correct) direction. It is fair to assume that such a failure to comply with the rules, either as a result of a lack of knowledge, or with full intent, can result in safety critical situations on bicycle infrastructure. These results suggest that it is important to note that it is not enough to focus research only on conflicts between motorised vehicles and bicycles on the road. It cannot be argued that other incidents are negligible.

7 Integration of the results to the TCI Model

According to the TCI Model, collisions occur when the task demands exceed the capability of the rider, which results in a high task difficulty (Fuller et al., 2008; Fuller, 2005). The authors stated that speed is one of the most influential factor on task demands. Performing the riding task at high speed is more demanding than it is at low speed, since the rider has less time for information processing and reaction (Fuller et al., 2008).

The results reported in Paper I showed that both groups of e-bike riders (pedelecs and S-pedelecs) did indeed travel faster than conventional cyclists, which increased the demands of the riding task for them. However, older e-bike riders were slower than their younger counterparts as well as younger conventional cyclists. Overall, elderly people were slower than middle aged and younger ones. It is therefore apparent that there might not necessarily be a higher risk for older riders of e-bikes, as is often assumed. The slow speed of the elderly could be an indication of compensation for their age-based limitations (which include reduced physical functions, slower reactions and perception, as well as visual impairments, Oxley et al., 2004). Due to the slower speed, the task difficulty remains on a manageable level, which helps riders to maintain control of the bicycle. As the results of Paper II suggest, slowing down is an appropriate (if probably unconscious) strategy, since the older cyclists did not experience more critical situations than the younger groups.

Papers III and IV showed that drivers underestimate the speed of e-bikes, because they chose smaller gaps in front of an approaching e-bike. According to the TCI model, the task demands could be exceeded if a driver misjudges the e-bike’s speed and turns suddenly in to their lane. From these results, a higher risk for e-bike riders may be assumed. At the same time, if in this situation the e-bike rider is an older rider, their reaction times are expected to be longer and their braking reactions slower than for younger riders. Therefore, crashes are much more likely for this specific group in this situation.

In Paper II, the influence of infrastructure type on SCEs was investigated and the results suggest that the risk of SCEs was very high for bicycle infrastructure. A lot of SCEs were observed when pedestrians suddenly crossed the path of the cyclist or e-bike rider. This lack of consideration for or awareness of the different road users can enhance the task demands. Similarly, physical characteristics of the infrastructure promote incidents between pedestrians and cyclists, since the pavement and bicycle infrastructure are not always separate. Thus pedestrians might cross or walk along the bicycle infrastructure unintentionally. The relatively high speed of cyclists and e-bike riders on pavements increased the risk of SCEs as well. Pavements are actually too narrow for a cyclist to get out of the way of or overtake a pedestrian, but higher speed of cyclists compared to pedestrians makes such manoeuvres necessary. Although not all of these problems should be solved through structural changes, problems are still caused by the infrastructure and its characteristics - the infrastructure has an influence on task demands and can enhance the difficulty of the riding task.

In conclusion, the TCI model is helpful to understand why both specific singular factors and also a combination of several factors can cause critical situations and subsequently induce crashes.

8 Implications

For each of the three traffic safety pillars some implications for road safety should be inferred from the findings. As it stands, the long-lasting impact of e-bikes on road safety can only be estimated. For Germany, reliable crash data are only expected on 2017 (Alrutz et al., 2015). However, based on the findings of Paper I regarding the higher speed of pedelecs (and particularly S-pedelecs) e-bikes might be assumed to be associated with a higher risk; hence S-pedelecs in particular might have an impact on road safety. So far, the impact of pedelecs may not be expected to be so strong, because most riders are currently elderly, whose riding speed is not so much higher than it is for conventional cyclists of the same age. However, future development will show how the situation will change as the user population of e-bikes also changes. E-bikes could become an attractive proposition for younger riders. Some recent studies have reported a growing acceptance of e-bikes among younger cyclists (Jellinek et al., 2013; Sinus, 2014). It has even been suggested that the e-bike is going from being a “rehabilitation vehicle” to a trendy accessory (Touring Club Schweiz, 2014). How this will influence the two wheeled traffic and road safety in the middle and long term is a matter of speculation. For the time being, it appears that the regulations in place which treat pedelecs like conventional bicycles and S-pedelecs like small motorbikes are appropriate. Bohle (2015) claimed: “Due to the fact that pedelec-users behave comparably to conventional cyclists, the classification of pedelecs 25 as bicycles is acceptable” (p. 7). However, S-pedelec users should be particularly informed about the obligation to wear a helmet and use the road itself, in order to reduce the danger to themselves and others. There is currently a need for a stronger enforcement of these regulations.

The high rate of illegal infrastructure usage could cause problems if the S-pedelec riders continue use bicycle infrastructure and the variation in speed between the different users increases. Amongst e-bike riders a lack of knowledge of the rules was observed in interviews with pedelec and S-pedelec riders (Bohle, 2015); the same was also found for cyclists (Huemer & Eckardt-Lieberam, 2015; Huemer et al., 2014). This could be one explanation for the high percentage of pavement usage by all bicycle types. Thus better education and dissemination of traffic rule knowledge by road safety campaigns or in training schemes is recommended (Jellinek et al., 2013). Moreover, stronger control and enforcement should be carried out to prevent conflicts between the different road users.

Because of the high number of SCEs away from the road itself, the research should also consider the conflicts on other infrastructure types. The focus of the statistics on bicycle crashes on the road seems unjustified. As shown by the results of the study of SCEs, there are a large amount of critical situations away from the road such that existing statistics only represent “the tip of the iceberg” (Juhra et al., 2012, p. 2026).

People who have already ridden a conventional bicycle and want to use a pedelec instead should receive training about the speed of e-bikes and how to handle them, especially if they have not ridden in a long time. Specialist bicycle dealers might operate as providers of initial instruction. Training schemes for the safe use of e-bikes are a very good approach and are already being offered by some traffic safety centres (e.g. Verkehrssicherheitszentrum Bielefeld, 2014; Verkehrswacht Coburg, 2014). It might be possible to implement special training schemes which are tailored for older people, as the largest user group of e-bikes, in order to teach them how to accelerate, cycle and brake safely. Offering this type of training seems necessary, as e-bikes differ from conventional bicycles due to their higher weight and the motor assistance.

In addition to training schemes, the development of special bicycles seems to be desirable due to the fact that elderly riders experience accidents while mounting and dismounting on the bike more frequently (Scheiman et al., 2010). In the Netherlands a special bicycle (SOFIE) for older riders was developed (Dubbeldam et al., 2015). This SOFIE bicycle helps cyclists to be balanced, and reduces the time on one leg significantly compared with a regular bicycle, in order to reduce the risk of falls. So-called intelligent bicycles (with ‘obstacle detection system’ and a ‘safe route advisory system’) can also help cyclists, especially the elderly. In the Netherlands a prototype of such an intelligent bicycle is currently being tested (de Hair, Kwakkernaat, Dubbeldam, & Engbers, 2015). Especially useful for older riders is rear-view assistance, which warns them of traffic from behind; they often have limited ability to rotate their head (Engbers et al., 2014).

Results of the experiments to gap acceptance and TTA judgements suggest that the underestimation of the speed of e-bike riders by other road users might result in conflict situations, especially at intersections. Analyses of crashes involving e-bikes supports this, as data show that in collisions with e-bikes, the opponent was found to have been at fault in 70% of all cases, compared with 61% for conventional bicycles. According to the literature, this suggests that others underestimate the speed of the e-bike rider (Scaramuzza et al., 2015). The findings indicate that there is no simple solution to the problem of a potential misperception of an e-bike’s approach. It might be possible to increase the distinctiveness of e-bikes through design changes, to allow for clearer differentiation between them and conventional bicycles. Of course, once market penetration is high enough for other road users to be more familiar with e-bikes, the speed of an e-bike may no longer be a surprise. Nevertheless also other road users should be made aware of the fact that pedelecs and S-pedelecs look like conventional bicycles, but could be faster. Road safety organisations are responsible for taking measures to educate other road users (Bohle, 2015). As it stands, the e-bike users themselves have to be prepared for other road users to turn or cross suddenly, and should ride with foresight.

Intersections were particularly implicated in e-bike crashes, and their design could contribute to improved safety – for example by the removal of visual obstacles for a good visibility over the whole intersection and into the contiguous traffic lanes (Scaramuzza et al., 2015). The findings reported in Paper II and in other field observations (Dozza & Werneke, 2014) showed a high number of SCEs with pedestrians and other cyclists. Due to this, researchers argued in favour of banning mixed infrastructure for pedestrians and cyclists without clear visible separation between these two groups (Jellinek et al., 2013).

E-bike riders stated that they tend to overtake other cyclists more frequently if they are riding an e-bike instead of a conventional bicycle (Dozza & Piccinini, 2014). In anticipation of a larger number of pedelecs (and hence greater variation in speeds) on bicycle infrastructure in the coming years, the width of bicycle infrastructure should be reconsidered and perhaps extended for new cycling facilities (Bohle, 2015; Scaramuzza et al., 2015). The configuration of bicycle infrastructure should allow overtaking manoeuvres by the faster cyclists and e-bike riders (Alrutz et al., 2015).

9 Conclusion

The findings of this dissertation suggest that all three factors that were considered (bicycle type, rider age and infrastructure characteristics) do indeed have an influence on the safety of cyclists in traffic. The results indicate that e-bike riders are faster than conventional cyclists. They also might be at a higher risk of crashing, as other road users may not perceive their speed correctly. The data show that elderly riders typically travel slower than younger ones, and their risk of being involved in safety critical events is not increased, despite their age. Different infrastructure types appear to have an effect each of on speed and crash risk, although there are not clear links between them.

Based on these findings, a number of suggestions were made. Well-designed training sessions can have the potential to help improve both bicycle control and knowledge of regulations, especially amongst the elderly. Likewise, technical innovations can make controlling the bicycle easier, and might allow for a clearer differentiation between conventional and electrical bicycles. Infrastructure improvements, such as wider cycling lanes or the removal of visual obstacles might reduce conflicts between cyclists and all other road users. It can be assumed that a combination of such measures will be able to contribute substantially to the enhancement of road safety of e-bike riders and cyclists of all age groups.

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PAPER I

THE GERMAN NATURALISTIC CYCLING STUDY - COMPARING CYCLING SPEED OF RIDERS OF DIFFERENT E-BIKES AND CONVENTIONAL BICYCLES

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THE GERMAN NATURALISTIC CYCLING STUDY - COMPARING CYCLING SPEED OF RIDERS OF DIFFERENT E-BIKES AND CONVENTIONAL BICYCLES

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Abstract

In recent years, the number of electric bicycles on European, American and especially Chinese roads has increased substantially. Today, 11% of all bicycles sold in Germany are e-bikes. Given their potential to reach higher maximum speeds, concerns have been raised about a possible increase in crash risk associated with e-bike use. However, as of now, it is unclear if and how often the potentially higher speed is actually reached in everyday cycling. As part of the German Naturalistic Cycling study we measured and compared the speed of three bicycle types (conventional bicycles, pedelecs (pedalling supported up to 25 km/h), S-pedelecs (pedalling supported up to 45 km/h)) under naturalistic conditions. Ninety participants, divided in three age groups, took part in our study. Participants used their own bikes or e-bikes. The bicycles were equipped with a data acquisition system, which included sensors to record speed and distance, as well as two cameras. Data was collected over a period of four weeks for each participant. Nearly 17,000 kilometres of cycling were recorded in total. The statistical analysis revealed significant differences in mean speed between all three bicycle types. Pedelec riders were, on average, 2 km/h faster than cyclists. S-pedelec speed was even 9 km/h higher. A similar pattern was also found when analysing free flow conditions and uphill or downhill cycling separately. The highest speed was measured on carriageways and bicycle infrastructure, regardless of bicycle type. Participants aged over 65 years rode significantly slower than younger participants. Data on acceleration from standstill largely confirm the differences between bicycle types and age groups. The results show that electric bicycles indeed reach higher speeds than conventional bicycles regularly. Although it is unclear if this also leads to an increase in crash risk, it can be assumed that the consequences of a crash might be, on average, more severe.

Keywords: e-bikes, speed, acceleration, infrastructure types, Naturalistic Cycling Study.

1 Introduction

In recent years, the distribution of electric bicycles (e-bikes) has increased continuously. Especially in China, the number of e-bikes has risen substantially (Bundesministerium für Verkehr Innovation und Technologie, 2013). A similar trend can be observed in the US and in Europe (Rose, 2012). In Germany, about 1.6 million electric bicycles are currently on the road (Zweirad-Industrie-Verband, 2014), and it is expected, that this number will increase even further (Jellinek, Hildebrandt, Pfaffenbichler, & Lemmerer, 2013). As a result of this development, questions have been raised regarding a potentially increased crash risk for e-bikes. One central concern that has been voiced repeatedly is the fact that these e-bikes can reach a higher speed than conventional bicycles, which might lead to a variety of problems (Bai, Liu, Chen, Zhang, & Wang, 2013; Jellinek et al., 2013; Skorna et al., 2010). Scaramuzza and Clausen (2010) estimated an increase of severe injuries of about 150%, and an increase of even 350% for fatalities, if the overall cycling mean speed would increase by 6 km/h as a result of the growing distribution of e-bikes.

Data on the speed of conventional bicycles have been inconsistent. Two US studies found comparable mean speeds of 18 km/h (Dill & Gliebe, 2008) and 16 km/h (Thompson, Rebolledo, Thompson, Kaufman, & Rivara, 1997). Other investigations from Europe have reported mean speeds between 12 km/h and 14 km/h for conventional cyclists (Dozza & Werneke, 2014; Menghini, Carrasco, Schüssler, & Axhausen, 2009). Up until now, only few studies have investigated the average speed of e-bikes. Results from China (Cherry & He, 2009; Lin, He, Tan, & He, 2007) suggest that e-bikes are considerably faster than conventional bicycles. Mean speeds were found to be 7 km/h (Lin et al., 2007) and 5 km/h (Cherry & He, 2009) higher, respectively. For users of a US bike share programme higher travel speeds were found for e-bikes (13 km/h) in comparison to bicycles (11 km/h) on carriageways, whereas e-bike speed was lower on shared use facilities (Langford, Chen, & Cherry, 2015). For Europe, a Swiss study (Paefgen & Michahelles, 2010) reported an e-bike mean speed of about 19 km/h, however lacked comparable data for conventional bicycles. An observational study in Germany recorded a mean speed of nearly 17 km/h for e-bikes (Alrutz, 2012, 2013), which was two to three km/h higher than for conventional bicycles.

Unfortunately, the term e-bike has been applied to a very broad range of vehicles, with a high variance in the support they provide, and subsequently with profound differences in the potential maximum speed. In China, some scooters with only rudimentary pedals are considered e-bikes (Cherry & Cervero, 2007). Such vehicles would hardly be called e-bikes by European standards. But also in Europe, different categories of electric bicycles exist. In Germany, we distinguish between so called pedelecs, which support pedalling up to 25 km/h (250W), and S-pedelecs, which support up to 45 km/h (500W) (Zweirad-Industrie-Verband, 2012). Similar categorisations (often with consequences for licensing, insurance etc.) exist in most European countries (Jellinek et al., 2013). It is obvious that comparisons of operating speed between different studies from different countries all over the world, with different traffic environments, different cyclist populations, and different bicycle categories are problematic.

Adding to this problem is the fact that the cited studies use a variety of different methodologies, each with their individual shortcomings and restrictions. Many investigations covered only a limited range of infrastructure types, as they either used a stationary (Jellinek et al., 2013; Lin et al., 2007; Thompson et al., 1997) or "floating vehicle" (Cherry & He, 2009) approach. This might result in a considerable bias in the data (limited infrastructure and traffic environment, bias in the observed cyclist populations, trip purposes etc.), and can limit the generalisability of the findings. Such observations also hamper the assessment of the influence of a variety of variables, as age, gender and even bicycle type have to be judged by an observer and cannot be directly collected (Jellinek et al., 2013; Lin et al., 2007). Other issues include limitations in subject samples or the lack of proper control groups (Paefgen & Michahelles, 2010).

The aim of this study was the investigation of speed (including acceleration) of electric bicycles in comparison to conventional bicycles. In order to avoid the described methodological issues, the naturalistic cycling methodology appeared to be most appropriate. In naturalistic observations, cameras and sensors are used to record the road users' usual behaviour to obtain data that is not contaminated by the influence of experimental manipulation. With motorised vehicles, *Naturalistic Driving Studies* (NDS) have been conducted for more than 20 years now (Dingus et al., 2006; Kessler et al., 2012; Lee, Olsen, & Wierwille, 2004). Only recently has the NDS approach been applied for the investigation of cyclist behaviour (so called *Naturalistic Cycling Studies*, NCS). Most NCS were interested in the identification of safety critical situations when riding a conventional bicycle (Dozza & Werneke, 2014; Johnson, Charlton, Oxley, & Newstead, 2010), while others focused on mobility behaviour or rider distraction (Gustafsson & Archer, 2013; Knowles, Aigner-Breuss, Strohmayer, & Orlet, 2012). So far, no NCS has been conducted that addressed the speed differences between different bicycle types. Our study investigated the speed and acceleration of conventional bicycles, pedelecs and S-pedelecs without restrictions, taking into consideration aspects such as infrastructure, road gradient and riders' age.

2 Method

2.1 Participants

Participants were recruited through newspaper ads or flyers in cycling shops. The applicants filled in a recruitment questionnaire, which included questions on their socio-demographic status and technical data of their bicycle, with special focus on the bicycle type (conventional bicycle, pedelec, S-pedelec). Applicants were selected for participation based on criteria such as bicycle type, frequency of usage and age. As we were especially interested in e-bikes, we tried to recruit as many e-bike riders as possible. However, since S-pedelecs are still rather rare (Preißner, Kemming, Wittkowsky, Bülow, & Stark, 2013; Zweirad-Industrie-Verband, 2013), there were relatively few applicants for this group. At the same time, we had a substantial number of candidates for the pedelec category. Those candidates were, on average, older riders, which is in line with the reported age structure of the overall pedelec rider population in Germany (Alrutz, 2013; Preißner et al., 2013). To ensure comparability of our different user groups, we selected users of conventional bicycles for participation matching the age of the pedelec riders. 90 cyclists took part, however data of five participants had to be excluded from analysis as the data sets were incomplete. 85 datasets (32 female, 53 male), divided in three age groups (see Table 1 for an overview), remained for analysis[2]. Gender was not equally distributed across the different bicycle types. Our S-pedelec riders were all male, whereas in the other two groups, distribution was more (although not fully) even (bicycle: 11 female, 17 male, pedelec: 21 female, 27 male). As participants were supposed to use their own bicycles for the study, we saw a wide range of different bicycle types. The majority of our participants' conventional bicycles were so called city bikes, with also a few mountain bikes. Only two pedelec riders owned a mountain bike style pedelec, the rest were all city bikes. All S-pedelec riders used trekking or city bikes. Nearly 60% of the e-bike riders reported to use a regular bicycle in addition to their e-bike. All participants received €100 for their participation.

[2] Due to the use of stricter criteria for the inclusion of datasets, the subject sample differs slightly from the published research report (Schleinitz et al., 2014). Consequently, values in descriptive statistics differ as well. However, the overall findings based on inferential statistics are identical.

Table 1. Overview of demographic data (N = 85).

	Cyclist			Pedelec rider			S-pedelec rider		
Age groups	*N*	*M age*	*SD age*	*N*	*M age*	*SD age*	*N*	*M age*	*SD age*
≤ 40 years	8	30.8	7.1	15	33.3	6.6	3	25.0	9.5
41 - 64 years	9	52.4	8.5	14	54.1	7.2	6	43.2	1.7
≥ 65 years	11	69.5	3.2	19	70.4	3.2	-	-	-
Total	**28**	**51.5**	**17.2**	**48**	**53.5**	**16.8**	**9**	**37.1**	**10.3**

2.2 Data Acquisition System (DAS)

Trained technicians installed and uninstalled a data acquisition system (DAS) on the participants' own bicycles. A speed sensor was installed on the front wheel to record speed and distance data (data rate 2 Hz). Two cameras (Type ACME FlyCamOne eco V2), placed in a small box, were mounted on the handlebar. One camera captured the forward scenery and the other the face of the cyclist. The videos were recorded at 30 frames per second with a resolution of 720x480 pixels (VGA). All data was stored on two SD-memory cards, one for video (32 GB) and one for speed data (4 GB). Participants started and stopped recording with a flip switch.

2.3 Procedure

The study was conducted in and around Chemnitz (Germany) from July to November 2012. Exposure to different weather conditions did not differ between the three bicycle types, as we made sure that during the whole period of data acquisition, the same proportion of conventional bicycles, pedelecs and S-pedelecs was instrumented. For each participant, data was recorded over a period of four weeks. Weather conditions varied from hot and sunny in summer to cold and icy in October. An individual appointment for the installation of the DAS was arranged with each participant. In order to check their level of cycling ability, the technician conducted a short cycling skill test with the participants. None of the participants showed any specific deficits. During the course of the observation period, participants were instructed to use their bicycles as they would do normally. They were supposed to record every single trip they made, regardless of trip purpose, trip duration, time of day or other factors. Necessary maintenance procedures like DAS repairs and exchange of storage media were carried out by our technicians. At the end of the observation period, another individual appointment was made for dismounting the DAS.

2.4 Data preparation

2.4.1 Sensor data

Data of the wheel sensors were collected for each trip to obtain data for speed and covered distance. Data of non-trip recordings (e.g. DAS still activated while the bike was already parked) were excluded from the analysis. To calculate operating speed, we followed the common procedure in removing all standstill situations (speed = 0 km/h) from the dataset (Cherry, 2007; Dill & Gliebe, 2008; Lin et al., 2007).

To analyse the cyclists' acceleration, we decided to look into situations in which the cyclist started from standstill. Due to the relatively low data rate (2Hz), reporting acceleration in m/s^2 appeared inappropriate. Instead, we described the development of speed immediately after a standstill situation, without the calculation of an actual acceleration metric. We analysed a window of 15 s after a bike started moving again. Only situations in which a speed of a least 5 km/h inside that window was reached were included in the analysis. If this was not the case, it had to be assumed that no normal acceleration had occurred (e.g. the bike was pushed).

2.4.2 Video data

To investigate the influence of different infrastructure characteristics on cyclists' speed, video material was annotated for each trip continuously for one week that was chosen randomly. The categories of infrastructure were based on definitions in German road traffic regulations (StVO, see Table 2). We also annotated free flow situations (no other road user in front of cyclist, no curves or other obstacles) and instances of clearly downhill and uphill riding.

The overall annotation procedure was based on Klauer, Perez and McClafferty (2011). All annotators received a special training. Discrepancies found by the senior annotators in spot checks were discussed and resolved in team meetings. In total, 1,023 videos with a duration of about 263 hours were annotated. The video annotations were synchronised with the sensor data in our database, so that the cyclists' speed could be linked to the infrastructure characteristics.

Table 2. Overview of the annotated categories of infrastructure.

Type of infrastructure	Description/Examples
Carriageway	Part of a road used by cars etc.
Bicycle infrastructure	Bicycle lane, bike path
Pavement	Footpath along the sides of a road
Pedestrian precinct	Pedestrian-only use, some or all automobile traffic prohibited
Unpaved	Forest path, field path
Miscellaneous	All other types of infrastructures i.e. parking facility, small path between buildings, path in allotment

3 Results

In order to assess the relationship between the different bicycle types and cycling speed without the confounding influence of age (and since we were not able to recruit older participants in the S-pedelec group, resulting in an empty cell in our design), we conducted analyses of covariance (ANCOVA) with participants' age as covariate. It has to be acknowledged that the ANCOVA regression slopes were not homogeneous in several cases. Therefore, we conducted additional ANOVAs, in which we included the age group as a factor (see Table 1), and omitted the S-pedelec group as a level of the factor bicycle type. All reported post-hoc pairwise comparisons were corrected for multiple comparisons (Bonferroni correction).

3.1 Dataset overview

Overall, we recorded 4,327 trips with a total distance of 16,873 kilometres during the four weeks of data collection. On average, each participant cycled about 198.5 km during the study. Although the S-pedelec riders appeared to have cycled longer total distances than the other two groups, an ANCOVA revealed no significant differences between the bicycle types, $F\,(2, 81) = 2.87$, $p = .062$, $\eta^2_p = 0.07$, (see Table 3). Age had also no significant influence on the distance cycled, $F\,(1, 81) = 2.73$, $p = .103$, $\eta^2_p = 0.03$. It has to be noted that, for all bicycle types (especially the S-pedelecs), the range in total distance travelled is considerable. For mean trip length, the ANCOVA revealed a significant difference between the bicycle types, $F\,(2, 81) = 5.91$, $p = .004$, $\eta^2_p = 0.13$, whereas no effect for age was found, $F\,(1, 81) = 0.41$, $p = .523$, $\eta^2_p = 0.01$. Trips on S-pedelecs (M = 7.3 km, SD = 4.4 km) were significantly longer compared to trips completed with pedelecs (M = 4.7 km, SD = 2.9 km, $p = .035$) and conventional bicycles

(M = 3.5 km, SD = 2.5 km, p = .003). Pecelec and bicycle trip length did not differ significantly from each other (p = .350).

Table 3. Mean total distance travelled in km per bicycle type and age group (N = 85).

	Bicycle (n = 28)				Pedelec (n = 48)				S-pedelec (n = 9)			
Age group	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
≤ 40 years	149.1	69.7	64.5	291.1	166.7	114.0	53.1	471.8	135.1	45.5	89.6	180.6
41 - 64 years	210.9	113.3	42.8	411.0	193.4	110.7	65.9	446.3	345.5	288.0	148.8	922.8
≥ 65 years	198.3	131.4	30.2	425.8	206.1	61.5	111.9	324.2	-	-	-	-
Total	**188.3**	**110.1**	**30.2**	**425.8**	**190.1**	**94.8**	**53.1**	**471.8**	**275.4**	**251.8**	**89.6**	**922.8**

3.2 Speed

3.2.1 Mean speed, free flow conditions and road gradient

Figure 1 displays the distribution of trip mean speed. In general, S-pedelec riders completed more trips with higher mean speed than the other two groups. The analysis of mean speed (see Table 4) strengthened this impression. S-pedelecs travelled at ca. 24.5 km/h on average, pedelecs at 17.4 km/h, and conventional bicycles only at 15.3 km/h. An ANCOVA revealed a significant effect of bicycle type, F (2, 81) = 15.33, p < .001, η^2_p = 0.28. Pairwise comparisons showed that all bicycle types differed significantly from each other (p ≤ .019). Participants' age had a significant influence on operating speed as well, F (1, 81) = 27.92, p < .001, η^2_p = 0.26.

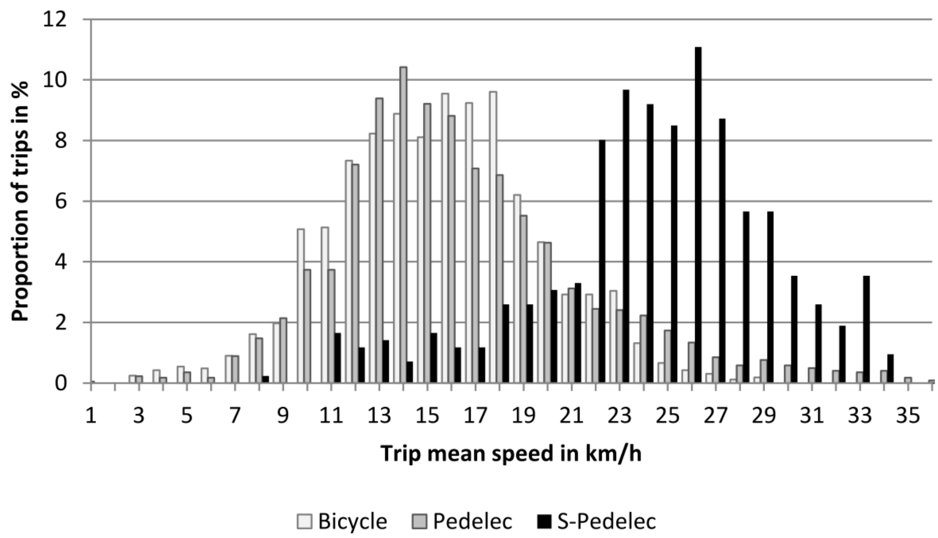

Figure 1. Proportion of trips made at different speeds (1 km/h steps) per bicycle type (N = 85).

Table 4. Mean speed per trip in km/h for different bicycle types and age groups (N = 85).

		Bicycle (n = 28)				Pedelec (n = 48)				S-pedelec (n = 9)			
Age group		*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Speed	≤ 40	16.6	3.4	13.1	22.0	20.5	5.2	12.9	31.0	23.4	0.9	22.6	24.3
	41-64	15.8	2.3	12.6	20.3	17.5	4.0	12.2	25.3	25.1	3.7	21.7	31.9
	≥ 65	13.9	2.6	10.1	18.4	14.8	1.9	12.2	18.6	-	-	-	-
	Total	**15.3**	**2.3**	**10.1**	**22.0**	**17.4**	**4.4**	**12.2**	**31.0**	**24.5**	**3.1**	**21.7**	**31.9**
Speed free flow	≤ 40	18.0	2.9	13.9	21.4	23.6	5.9	14.5	33.1	22.1	3.5	18.7	25.7
	41-64	17.6	3.4	13.6	25.4	18.6	4.5	13.3	28.0	26.3	4.1	22.1	33.5
	≥ 65	13.6	2.8	9.7	17.9	15.6	2.5	11.3	20.5	-	-	-	-
	Total	**16.1**	**3.6**	**9.7**	**25.4**	**19.0**	**5.5**	**11.3**	**33.1**	**24.9**	**4.2**	**18.7**	**33.5**
Speed uphill	≤ 40	14.5	3.1	10.8	19.6	20.4	5.1	13.9	31.8	20.7	1.9	19.4	22.8
	41-64	13.9	4.0	9.3	23.2	16.1	3.2	9.6	22.1	22.2	4.4	16.8	28.9
	≥ 65	10.9	2.1	7.6	14.0	13.5	2.2	10.6	17.3	-	-	-	-
	Total	**12.9**	**3.4**	**7.6**	**23.2**	**16.4**	**4.6**	**9.6**	**31.8**	**21.7**	**3.7**	**16.8**	**28.9**
Speed down-hill	≤ 40	19.6	3.2	14.5	24.6	26.9	7.0	18.5	42.9	27.0	2.6	25.1	29.9
	41-64	20.6	2.3	16.8	24.5	21.2	5.6	11.4	28.7	28.3	3.1	25.7	34.4
	≥ 65	16.7	3.6	11.9	21.7	18.5	2.4	15.2	22.3	-	-	-	-
	Total	**18.8**	**3.5**	**11.9**	**24.6**	**21.9**	**6.2**	**11.4**	**42.9**	**27.9**	**2.9**	**25.1**	**34.4**

For all bicycle types, the speed under free flow conditions (n = 84, one participant was not recorded riding under free flow conditions) was in general slightly higher than mean speed (Table 4). The ANCOVA showed a significant effect of bicycle type, F (2, 80) = 8.54, p < .001, η^2_p = 0.18, as well as a significant influence of age as covariate, F (1, 80) = 34.77, p < .001, η^2_p = 0.30. Pairwise comparisons showed that riders of conventional bicycles rode significantly slower than the riders of e-bikes (both p ≤ .10). There was no significant difference between pedelec and S-pedelec.

As expected, road gradient had an influence on the cyclists' speed as well (Table 4). When riding downhill, our participants were, on average, 5.8 km/h faster than when cycling uphill, F (1, 81) = 30.90, $p < .001$, $\eta^2_p = 0.28$. We again found significant effects of bicycle type, F (2, 81) = 12.88, $p < .001$, $\eta^2_p = 0.24$ and age, F (1, 81) = 33.09, $p < .001$, $\eta^2_p = 0.29$. The speed of the conventional bicycles differed significantly from the speed of the other two types (both $p \leq .001$), whereas there was no difference between pedelec and S-pedelec. There was no significant interaction between bicycle type and road gradient.

3.2.2 Mean distance travelled at higher speed

In addition to the assessment of differences in mean speed, we analysed to what extent our cyclists travelled at a higher speed. For this purpose, the distance covered at speeds above 20 km/h, 25 km/h and 30 km/h was related to the total cycling distance of each group (see Figure 2). As expected, S-pedelec riders covered a much higher proportion of their overall mileage at the higher speed levels. More than 80% of their total cycling distance was completed at a speed of 20 km/h or above, and still 34% with a speed of 30 km/h or higher.

Separate ANCOVAs revealed a significant main effect for bicycle type on each of the three speed levels (an overview of all effects can be found in Table 5). Pairwise comparisons showed significant differences between all three bicycle types for the 20 km/h level (all $p \leq .031$). At 25 km/h and 30 km/h, only the difference between S-pedelecs and the other two bicycle types was significant (all $p < .001$).

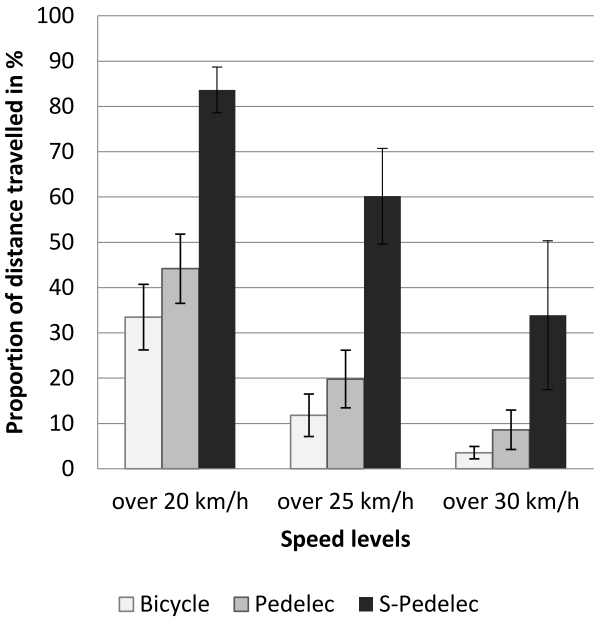

Figure 2. Proportion of distance travelled at speeds above 20 km/h, 25 km/h and 30 km/h per bicycle type (N = 85).

Table 5. Summary of all ANCOVA results for the three higher speed levels (N = 85).

		F	p	η^2_p
over 20 km/h	Bicycle type	13.06	**<.001**	0.24
	Age group	42.02	**<.001**	0.34
over 25 km/h	Bicycle type	19.78	**<.001**	0.32
	Age group	31.66	**<.001**	0.28
over 30 km/h	Bicycle type	13.48	**<.001**	0.25
	Age group	9.46	**.003**	0.11

3.2.3 Speed on different types of infrastructure

Table 6 displays the mean operating speed and the total distance cycled on each of our annotated types of infrastructure. The analysis is only reported at a descriptive level, as cell sizes vary considerably. Also, there is a wide variation in how often and how long each individual cyclist travelled on a specific infrastructure category, so participants' contributions to the cells' mean values are highly variable. Because of that, we decided to abstain from inferential statistics for this analysis.

S-pedelec riders cycled fastest on all types of infrastructure. The highest speed was measured when participants were travelling on the carriageway or bicycle infrastructure. Only for these two infrastructure types, we found a difference between conventional bicycles and pedelecs, whereas for all other categories, the mean speed were more or less equal. For all bicycle types, the speed recorded on the pavement and in pedestrian precincts was relatively high, although in Germany it is not legal to cycle on such infrastructure (with few exceptions). Also conspicuous was the high speed of S-pedelecs on bicycle infrastructure, especially when compared to the other two bicycle types. The use of S-pedelecs on bicycle infrastructure is illegal, yet our participants covered 18% of their total mileage there.

Table 6. Mean speed per trip in km/h on different types of infrastructure per bicycle type (N = 85).

Infrastructure type	Bicycle				Pedelec				S-pedelec			
	N	M	SD	Σ km	N	M	SD	Σ km	N	M	SD	Σ km
Carriageway	28	16.4	2.7	640.8	48	18.8	4.4	1,387.7	9	25.6	2.8	331.9
Bicycle infrastructure	27	16.7	4.0	204.1	42	18.4	4.7	328.1	6	23.6	2.3	60.3
Pavement	28	13.3	3.0	126.6	48	13.9	4.8	201.0	7	17.6	3.2	22.5
Pedestrian precinct	17	12.7	4.0	17.8	15	11.1	2.8	15.3	2*	19.8	2.9	1.5
Unpaved	15	13.7	4.7	120.1	31	14.5	5.0	189.0	5	16.4	3.1	11.8
Miscellaneous	27	9.9	2.2	44.1	48	9.4	3.3	56.1	9	14.2	1.6	11.1

*Note: Only few instances of cycling in pedestrian precincts were recorded for S-pedelec riders.

3.2.4 Influence of age on speed

To analyse the effect of age in more detail, ANOVAs that included the age group (see Table 7) as a factor were calculated only for conventional bicycles and pedelecs. For mean speed, the analysis showed a significant main effect of the factor age group (n = 76), F (2, 70) = 9.02, p < .001, η^2_p = 0.21 (Figure 3, top left). Pairwise comparisons showed a significant difference between our older and younger group (p < .001). ANOVAs analysing speed under free flow conditions (n = 75, Figure 3 top right), and speed dependent on road gradient (n = 76, Figure 3, bottom) also showed this age effect, F (2, 69) = 14.18, p < .001, η^2_p = 0.29 and F (2, 70) = 13.53, p < .001, η^2_p = 0.28. Pairwise comparisons again showed in both cases that the older group differed significantly from the younger one (both p < .001), but also from the 41-64 year olds ($p \leq$ .014). We found no significant interactions between age group and any other variable for any of the ANOVAs.

A similar pattern was also found for the mean total distance travelled at a higher speed level (see Table 7). Again, the ANOVAs confirm the effect of age group (all $p \leq$ .006; η^2_p = 0.13 - 0.24). Post-hoc comparisons showed that older participants differed significantly from the younger participants (all $p \leq$ .006) in all three speed levels. At the 20 km/h level, there was also a difference between the older participants and the 41 to 64 years group (p = .006).

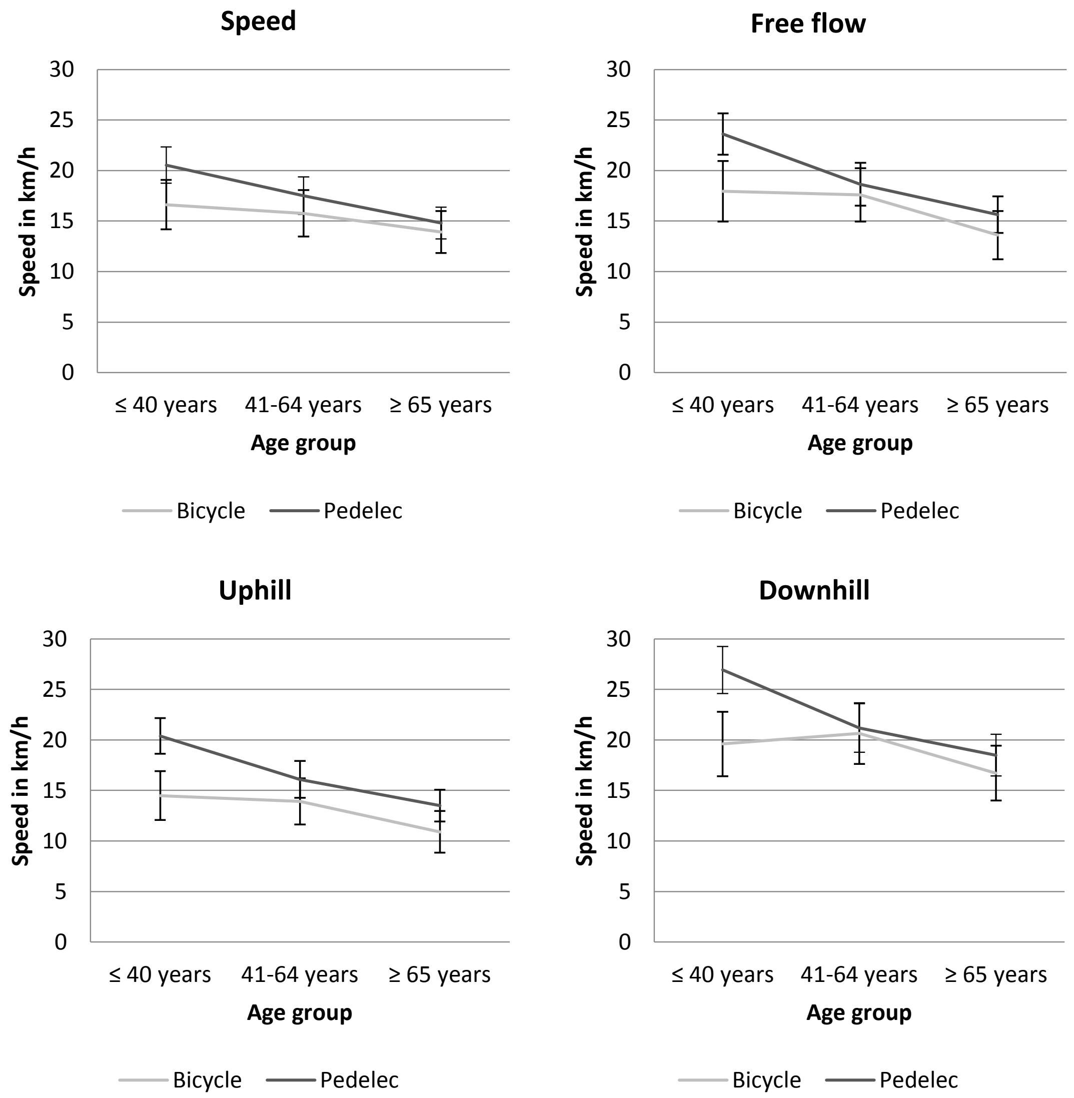

Figure 3. Overall mean speed (top left), speed under free flow conditions (top right) and speed dependent on road gradient (bottom) per bicycle type (conventional bicycle and pedelec only) and age group (n = 76).

Table 7. Proportion of total distance travelled at high speed levels for bicycle types and age groups (n = 76).

		Bicycle (n = 28)		Pedelec (n = 48)		Total (N = 76)	
		M	*SD*	*M*	*SD*	*M*	*SD*
Proportion over 20 km/h in %	≤ 40 years	41.5	22.1	63.1	24.1	55.6	25.2
	41-64 years	36.0	16.2	48.9	25.3	43.9	22.7
	≥ 65 years	13.6	16.4	25.8	15.0	25.7	15.3
	Total	**33.5**	**18.7**	**44.2**	**26.3**	**40.2**	**24.3**
Proportion over 25 km/h in %	≤ 40 years	17.3	17.9	36.6	26.4	29.8	25.2
	41-64 years	12.1	11.0	19.6	19.8	16.7	17.0
	≥ 65 years	7.6	5.9	6.7	4.2	7.1	4.8
	Total	**11.8**	**12.1**	**19.8**	**22.0**	**16.9**	**19.2**
Proportion over 30 km/h in %	≤ 40 years	5.0	5.1	19.6	22.6	14.5	19.6
	41-64 years	3.5	3.5	6.0	6.7	5.0	5.7
	≥ 65 years	2.6	2.0	1.9	1.5	2.1	1.7
	Total	**3.6**	**3.6**	**8.6**	**15.0**	**6.7**	**12.3**

3.3 Acceleration

In Figure 4 (left), acceleration from standstill is illustrated for the three bicycle types (N = 85). It is clearly visible that S-pedelec riders accelerated much stronger than the other two groups. After 2.5 s, they were, on average, more than 2 km/h faster than conventional bicycles and pedelecs, after 5 s, the difference was nearly 5 km/h. In contrast, there appears to be no difference between conventional bicycles and pedelecs. It has to be acknowledged that, as we have shown previously, speed and age are confounded. Since the S-pedelec sample was, on average, younger than the other samples, the actual effect of bicycle type might be smaller than the graph suggests.

Figure 4 (right) displays the relationship between age group and acceleration (similar to the analysis of the effect of age on speed, only conventional bicycles and pedelecs are included, *n* = 76). As the results on operating speed would have suggested, the three different age groups also differed in terms of acceleration. The youngest group reached certain speed levels much earlier than the other two. There also seems to be a difference, however less pronounced, between the two other groups, with the oldest cyclists having accelerated the weakest.

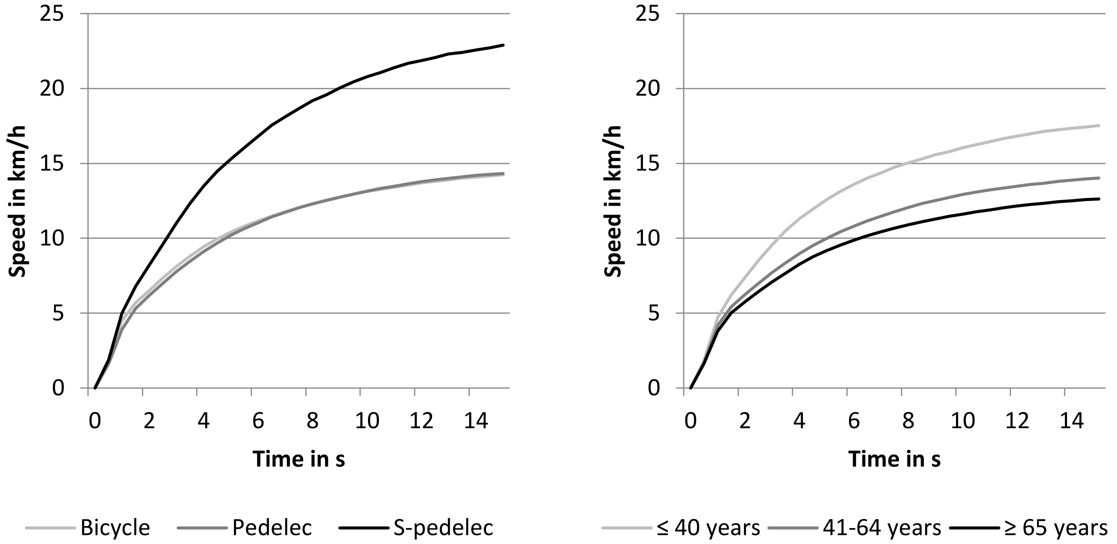

Figure 4. Acceleration per bicycle type (left, *N* = 85) and age group (right, conventional bicycle and pedelec only, *n* = 76).

4 Discussion and conclusion

Aim of this study was to investigate the speed and acceleration of electric and conventional bicycles under naturalistic conditions. We differentiated between electric bicycles that provide support up to 45 km/h (so called S-pedelecs) and 25 km/h (pedelecs). The results showed a very clear pattern. S-pedelecs travelled at a higher mean speed overall and under various specified conditions. They completed a much higher number of their trips at high mean speeds (Figure 1), just as they completed a much larger portion of their total travelling distance at higher speeds (Figure 2). In addition, they appeared to accelerate stronger than conventional bicycles and pedelecs. Furthermore, as speed limits of 30 km/h might impact especially on the behaviour of faster cyclists (i.e. S-pedelec riders), the potential mean speed might be even higher under different conditions. We also found significant differences in multiple measures between pedelecs and conventional bicycles, although less pronounced. Somewhat surprising was the absence of a difference between pedelecs and conventional bicycles with regard to their acceleration behaviour. This might interpreted as an indication that, when accelerating from standstill, the pedelec riders used the assistance that the motor provided mainly to reach their desired speed easier, not earlier. In general, however, the results support findings from previous studies, which compared conventional bicycles to either a form of S-pedelec (Cherry & He, 2009) or pedelec (Jellinek et al., 2013; Onnen-Weber, Schramek, & Butz, 2012). It appears that, at least to some degree, cyclists use the support that e-bikes provide to ride faster.

A similar pattern emerged when we looked into the effect that different types of infrastructure might have on cycling speed. The S-pedelec riders cycled fastest on each type of infrastructure. In contrast, pedelec and conventional bicycle speed differed only on the carriageway and cycling infrastructure. This suggests that the potential of pedelecs can be exploited especially under free flow conditions, which are hardly found on infrastructure other than carriageway or bike path. It has to be acknowledged that we found a substantial amount of illegal infrastructure use in our dataset. Despite the fact that S-pedelecs are not allowed to use bike paths in Germany, our S-pedelec riders still used them to a considerable degree, and at a much higher speed. As a result, a previously uncommon variation in speed is introduced to the cycling infrastructure, which certainly increases the potential for conflicts. The use of infrastructure usually reserved for pedestrians appears to be another problem. However, mean speed on the pavement and pedestrian precincts at least suggest that cyclists adapt and slow down.

As anticipated (Jellinek et al., 2013; Lin et al., 2007), cyclists' age had a significant influence on their speed. When analysed in separate groups, participants 65 years and older were slowest overall, and travelled the shortest distances at higher speeds, whereas participants 40 years or younger produced the highest mean speed and the largest proportion of riding at higher speeds. Pedelec riders in the oldest group were, on average, slower than the riders of conventional bicycles in the two other age groups. It appears that the concern that older pedelec riders might be cycling at a speed beyond their control is mostly unfounded. Of course, individual cases and situations in which control is lost due to excessive speed might still occur, but so they do for younger cyclists.

We have to acknowledge that the uneven distribution of gender in the different groups of bicycle users might have had a confounding effect on the measured mean speed. Previous observations have found a higher speed for male cyclists compared to female riders (Lin et al., 2007). However, current S-pedelec riders are predominantly male, so the bias in our sample accurately reflects the current user population. In addition, the potential of a self-selection bias due to the recruitment of volunteers cannot be denied. Especially for the older participants, it might be suspected that especially healthy and fit riders might be overrepresented. Consequently, mean speed, especially of older riders, might have been slightly overestimated when compared to the complete cyclist population.

The question of whether their overall higher speed makes e-bike riders more accident prone remains yet to be answered. Chinese statistics suggest that the number of e-bike related injuries and fatalities increased in recent years, whereas the number decreased for overall road traffic and conventional bicycles (Feng et al., 2010; Zhang, Cui, Gu, Stallones, & Xiang, 2013). However, it is unclear if the underlying cause is indeed a higher crash rate of e-bikes, or rather a higher crash severity. Siman-Tov, Jaffe and Peleg (2012) hypothesised that cycling speed might be related to a higher likelihood of specific types of injury. Based on Nilsson's power model that relates speed to road accidents, it can be assumed that a higher speed results in a higher crash risk as well as injury severity (Aarts & van Schagen, 2006; Elvik, Christensen, & Amundsen, 2004). Even if the actual cycling mean speed changed only moderately, a higher rate of injuries and fatalities would have to be expected. Especially for S-pedelecs, this aspect needs to be considered when discussing about road regulations.

The actual road safety impact of e-bikes and their potential to reach higher speeds can, at this stage, be only predicted in very broad terms. Given the difference in the user populations (which is not reflected in our matched participant sample), it is not unreasonable to assume that currently, e-bikes do not cause any change in cycling mean speed at all. However, there is some evidence that the acceptance of e-bikes is growing also among younger cyclists (Jellinek et al., 2013). It has even been suggested that the e-bike is going from being a "rehabilitation vehicle" to a trendy accessory (Touring Club Schweiz, 2014). In which way this will change two wheeled traffic and road safety in the middle and long term is a matter of speculation. For the time being, it appears that the regulations in place (treat pedelecs like conventional bicycles, S-pedelecs like small motorbikes) are appropriate. It only seems that, especially for S-pedelecs, there is the need for a stronger enforcement of these regulations.

5 Acknowledgments

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Paper II

Conflict partners and infrastructure use in safety critical events in cycling - Results from a naturalistic cycling study

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CONFLICT PARTNERS AND INFRASTRUCTURE USE IN SAFETY CRITICAL EVENTS IN CYCLING- RESULTS FROM A NATURALISTIC CYCLING STUDY

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Abstract

Accident statistics show that cyclists are at considerable risk of being involved in a crash. However, statistics based on police reports are often heavily biased towards on-road, bicycle-motor vehicle crashes. Crashes that do not involve motorised vehicles or that occur on other types of infrastructure are neglected. Naturalistic cycling methodology appears to be a promising approach to address these issues. The goal of this study was to identify and classify safety critical cycling events involving a variety of conflict partners and covering all types of infrastructure. Thirty-one participants in three age groups had their own bicycles equipped with a data acquisition system. Participants rode their modified bike as usual for a period of four weeks. Over 1,600 trips were recorded overall. We were able to identify 77 safety critical events during the observation period. Only 43% of these events involved motorised vehicles as conflict partners. Conflicts with other cyclists and pedestrians accounted for about 57% of the situations. Likewise, less than 35% of the events occurred on-road. The data show that although motorised vehicles are still the single biggest threat to cycling safety, and roads still constitute one of the most crash prone types of infrastructure, the importance of crashes that do not involve motorised road users or occur not on-road should not be underestimated.

Keywords: Bicycle, Conflicts, Crashes, Critical Events, Cyclist Behaviour

1 Introduction

With 71 million bicycles (incl. electric bicycles) in German households, a number that has increased by three million since 2007 (Zweirad-Industrie-Verband, 2013), nearly every German citizen owned a bicycle in 2012. Cycling is expected to become even more popular in the coming years (Statistisches Bundesamt [Destatis], 2013), which makes cyclists a non-negligible part of road traffic. As a consequence thereof, the number of cyclist fatalities in Germany increased about three percent in the last twenty years (Statistisches Bundesamt [Destatis], 2013). In Europe, an increase of six percent was recorded just from 2010 to 2012 (European Commission, 2014). Cyclists constitute the second-most accident and fatality prone road user group (Statistisches Bundesamt [Destatis], 2012a, 2012b). It is vital to reach a better understanding of the factors that might contribute to cycling crashes. What are the circumstances that lead to safety critical events (SCE)? What types of infrastructure are particularly dangerous? And who are the conflict partners? Unfortunately, as Walker (2011) notes: "With most aspects of bicycling research, the best we currently have are hints and incomplete stories." (p. 367). While some specific aspects have been well researched, the overall image is patchy at best. One of the reasons is that until recently, the available research methods have not allowed researchers to draw a complete picture of cycling crashes or cyclist behaviour.

1.1 Assessing safety risks for cyclists

Previous research mainly employed four different methods for investigating cyclists' risk in traffic: 1) surveys or interviews with cyclists, 2) analysis of accident statistics or in-depth accident investigations, 3) hospital data, and 4) local observation. In surveys and interviews, cyclists are asked to recall safety critical situations from memory (Bacchieri, Barros, Dos Santos, & Gigante, 2010; Chaurand & Delhomme, 2013; Washington, Haworth, & Schramm, 2012). These methods help gain deeper insight into cyclists' subjective experiences and help identify the factors that influence the perceived threat. For example, cyclists report a higher level of perceived threat as a result of risky motorist behaviour (e.g., failing to yield, not signalling when turning, tailgating, red light running) as compared to situations in which the same behaviour would be exhibited by a cyclist (Chaurand & Delhomme, 2013). Roundabouts are also perceived as a cause of threat, especially when a car is entering or exiting while a cyclist moves around (Møller & Hels, 2008). Likewise, mixed traffic with other road users is experienced as less safe than bike paths (Kolrep-Rometsch et al., 2012). However, such subjective reports are highly vulnerable to the influence of recall biases. One of the consequences can be an underreporting of less severe events (Bacchieri et al., 2010). Especially in cases in which older participants are asked to report the occurrence of rare events over a long period of time (such as crashes or critical events), data validity is questionable (Hagemeister & Tegen-Klebingat, 2012). Social desirability is another problem that can lead to systematic distortions in the data, as road users tend to conceal their own risky behaviour (Bacchieri et al., 2010).

The investigation of accident statistics based police records, provides, at first glance, a more objective approach for assessing risk factors in cycling crashes (e.g. Alrutz et al., 2009; Atkinson & Hurst, 1982; Boufous, de Rome, Senserrick, & Ivers, 2012; Martínez-Ruiz et al., 2013; Pfaffenbichler, 2011). In-depth investigations (e.g. GIDAS, SafetyNet) add further information by assessing a relatively small sample of crashes in greater detail (e.g. Orsi, Ferraro, Montomoli, Otte, & Morandi, 2014; Otte, Jänsch, & Haasper, 2012; SafetyNet, 2009). Major risk factors that have been identified through the investigation of crashes include specific rider and driver traits and states (e.g. age, intoxication), intersections (and here, especially roundabouts), specific traffic cycling and driving manoeuvres (e.g. being overtaken, crossing, turning, speeding), environmental conditions (e.g. visual conditions), and the state of the bicycle (e.g. no lighting, defective brakes; Boufous et al., 2012; Candappa et al., 2012; Daniels, Nuyts, & Wets, 2006; Martínez-Ruiz et al., 2013; Orsi et al., 2014). These factors have been linked to more frequent and / or more severe accidents. However, accident reports as well as in-depth investigations rely on retrospective accounts of the incident. These are prone to several forms of bias, which raises questions about the interpretation of findings based on these statistics. In addition, whereas it can be assumed that fatal accidents are fully captured in accident statistics, the potential underreporting of specific types of non-fatal bicycle accidents must be considered a serious issue (OECD/International Transport Forum, 2012; Tin Tin, Woodward, & Ameratunga, 2013). It is very likely that minor accidents without seriously injured conflict partners remain undocumented (Elvik & Mysen, 1999). Likewise, non-motorised vehicle accidents are often not reported to the police, and hence do not appear in official statistics (OECD/International Transport Forum, 2012; Twisk & Reurings, 2013). According to de Geus et al. (2012), only 7% of non-severe (minor injuries which lead to hospitalisation) bicycle accidents are registered in official accident statistics in Belgium. De Mol and Lammar (2006) showed that only 50% of traffic accidents in which cyclists are hospitalised are reported in European police statistics. This underreporting can lead to a severe bias in accident statistics, as the differences between bicycle crashes as they appear in official accident statistics and cycling injury data as they are collected by hospitals show (Lopez, Sunjaya, Chan, Dobbins, & Dicker, 2012). For instance, German accident data indicate that motorised vehicles are involved in more than three quarters of collisions that result in injury to cyclists (Statistisches Bundesamt, 2011). However, investigations of hospital data suggest that this rate might actually be below 40% (Juhra et al., 2012).

Compared to crash investigations, hospital data can contribute to a better understanding of accidents, especially of minor or single bicycle accidents (Juhra et al., 2012; Niska, Gustafsson, Nyberg, & Erikson, 2013). These datasets contain a lot of the information that is also found in crash reports, but additionally include incidents that are not severe enough to be reported to the police. In addition, they include detailed information on the consequences of crashes, such as crash severity and specific injury type (Dennis, Ramsay, Turgeon, & Zarychanski, 2013; Short & Caulfield, 2014). It has been found that injuries of the lower extremities are particularly frequent, and were often the result of direct collisions with a motorised vehicle (Richter, 2005). Head injuries are common as well (Richter et al., 2007), and are reported to have been the cause of death in up to 70% of single bicycle accidents (Niska et al., 2013). However, like crash investigations, hospital data are prone to bias as they also rely on retrospective accounts of the incident. And even though a larger percentage of overall crashes is included, researchers have criticised those data because information about outpatient treatment is often not included (Haileyesus, Annest, & Dellinger, 2007; Teschke et al., 2012). While a combination of hospital data and crash statistics can certainly provide a more comprehensive picture (Cryer et al., 2001; Twisk & Reurings, 2013), the problem remains that the incident in question has not actually been observed or recorded by an independent party.

Observational studies usually do not suffer from such biases. In most cases, cameras are placed in hidden locations to observe defined environments, such as intersections (Bai, Liu, Chen, Zhang, & Wang, 2013; Monsere, Mcneil, & Dill, 2012; Summala, Pasanen, Räsänen, & Sievänen, 1996) or one-way streets (Bjørnskau, Fyhri, & Sørensen, 2012). This method is especially useful for investigating accident black spots or specific phenomena like *Red Light Running* (Johnson, Newstead, Charlton, & Oxley, 2011). Observational studies on cycling accidents with turning cars found that a simple lack of sight or shoulder checks by the motorist (Kolrep-Rometsch et al., 2012), or more specific deficiencies in their visual scanning behaviour (Räsänen & Summala, 1998) might be blamed for a vast number of turning crashes. Observations of bicycle paths have shown that crossing pedestrians were the most common conflict partner (van der Horst, de Goede, de Hair-Buijssen, & Methorst, 2014). However, as cyclists and their behaviour outside the predefined environment are not observable, the approach cannot provide a complete picture of dangerous traffic situations. For example, it is likely that in the observation of intersections, the proportion of conflicts with motorised traffic might be higher compared to the share of such conflicts overall.

Field studies of traffic behaviour represent a promising approach for overcoming the limitations of the aforementioned methods. For nearly two decades, so called *Naturalistic Driving Studies* (NDS) have used cameras and sensors to record drivers' behaviour in their everyday and accustomed driving environment to obtain externally valid data that is not contaminated by experimental manipulation or the apparent presence of a researcher. However, even in research in which data are collected for hundreds of drivers over multiple years, crashes rarely observed. Therefore, researchers rely mostly on so called safety critical events as a proxy, an approach that is based on the 'Heinrich triangle' (Heinrich, Petersen, & Roos, 1980) and which is supported e.g. by Guo, Klauer, McGill, & Dingus, (2010). SCEs can be defined as "[s]ituations (including crashes) that require a sudden, evasive manoeuvre to avoid a crash or to correct for unsafe acts performed by the driver himself/herself or by other road users" (Bagdadi, 2013, p. 118). The most prominent examples to date are the *100-Car Study* (Dingus et al., 2006; Neale, Dingus, Klauer, Sudweeks, & Goodman, 2005) and the recently completed SHRP2 project(Campbell, 2013), which focused specifically on accidents and critical situations in car driving. A similar project is also under way in Europe, in which not only cars and trucks, but also motorised two-wheelers are part of the sample(Eenink, Barnard, Baumann, Augros, & Utesch, 2014). Given that data in NDS are not based on subjective information, results are not influenced by recall bias or social desirability. Behaviour in traffic is recorded in its entirety, so there is no systematic underreporting of several types of incidents or accidents. Consequently, an observation of factors that precede and influence SCEs becomes possible; thereby, allowing for a comprehensive understanding of such situations.

1.2 Naturalistic Cycling Studies

Based on the NDS methodology, in recent years, a handful of so called *Naturalistic Cycling Studies* (NCS) investigated aspects of mobility and cycling behaviour (Dozza & Werneke, 2014; Gustafsson & Archer, 2013; Johnson, Charlton, Oxley, & Newstead, 2010; Knowles, Aigner-Breuss, Strohmayer, & Orlet, 2012). Johnson et al., (2010) recorded 13 Australian commuters on their commuter cycling trips using helmet cameras for a maximum of 12 hours each. Overall, two collisions, six near-collisions and 46 critical incidents were classified, all of them involving another motorised road user. In nearly 90% of the situations, drivers were judged to have been at fault. About 70% of the events occurred at an intersection or were annotated as intersection-related.

A similar study investigating SCEs was conducted in Sweden (Dozza & Werneke, 2014). Sixteen cyclists rode test bicycles equipped with recording instruments and used them as substitutes for their own bikes for a period of two weeks. Participants were required to press a button on the handlebar to indicate any SCE they experienced. In the analysis, intersections and situations in which other road users crossed the bicyclist's route were identified as major risk factors.

While previous projects successfully demonstrated the feasibility of NCS in general, most of them did not fully utilize the potential of this methodology. Small sample sizes (e.g. $N = 5$, Knowles et al., 2012) or lack of behavioural or demographic representativeness in the sample (e.g. sample of working age cyclists that used their bikes primarily for commuting, see Gustafsson & Archer, 2013; Johnson et al., 2010) limit the external validity of the results. Others have further reduced external validity by placing restrictions on the types of trips that would be recorded and analysed, e.g. excluding off-road trips, such as trips on bike paths or on the pavement (Johnson et al., 2010). The focus on specific user groups, types of infrastructure and types of trips considerably limits the generalisability of findings. In particular, due to general sociodemographic trends, the number of elderly cyclists has increased and further increases are expected (Kubitzki & Janitzek, 2009; Steffens, Pfeiffer, & Schreiber, 1999). However, this trend has not been reflected in the participant samples of previous studies. People cycle for reasons other than transportation (Moudon et al., 2005) and cycling does not only occur on the road (Dill & Carr, 2003); yet, so far, this has been the focus of naturalistic cycling studies. Therefore, the goal of our study was to identify and describe SCEs (and crashes) in cycling for all kinds of trips, across all types of infrastructure, and with a participant sample that also included older cyclists using the naturalistic cycling methodology. Of specific interest were the conflict partners that are involved in SCEs, and the types of infrastructure on which such events occur.

2 Method

2.1 Participants

2.1.1 Participant recruitment

We recruited participants for the NCS through different media, including ads in newspapers and flyers in cycling shops. The prospective participants completed a recruitment questionnaire, which included questions gathering contact information, socio-demographic status and bicycle technical data. Also, as part of the project, a sample of electric bike users was recruited, which is not a subject of this paper. Potential participants were required to use their bike at least three days per week. In addition, we tried to recruit at least ten riders for each of our three age groups (see Table 1).

2.1.2 Participants

A total of 32 cyclists (divided in three age groups - 40 years and younger, 41 - 64 years, 65 years and older) took part in the study. We had one dropout, which left us with 31 participants with usable data (see Table 1). As we had only a few female applicants, gender was not distributed evenly in the sample. Most participants reported owning two or more bicycles in their households. Thirty of them had a driver licence. All participants received monetary compensation of 100€.

Table 1. Sample overview.

Age group	*M age*	*SD age*	*Min age*	*Max age*	Male	Female	**Total**
≤ 40 years	30.7	6.2	24	39	5	5	**10**
41 to 64 years	52.4	8.0	41	62	7	3	**10**
≥ 65 years	69.5	3.2	65	74	7	4	**11**
Total	**51.5**	**17.2**	**24**	**74**	**19**	**12**	**31**

2.2 Data Acquisition System (DAS)

A small box containing two cameras (Type ACME FlyCamOne eco V2) was installed on the handlebars of the participants' bicycles. One camera recorded the face of the cyclist while the other one was forward facing. The videos were recorded with a resolution of 720x480 pixels (VGA) at 30 frames per second. In addition, speed sensors were installed on the front wheel (2 Hz recording rate). All data were stored on two SD-memory cards, one for video (32 GB) and one for speed data (4 GB). Recording was started and stopped with a flip switch. Trained technicians installed and uninstalled the DAS on participants' bicycles.

2.3 Procedure

The study was carried out in and around Chemnitz (Germany). Participants were instructed to use their own bicycles. Data were recorded over a period of four weeks for each participant between July and November 2012. Participants were instructed to use their bicycle as usual and were directed to record all their trips with the DAS. Weather conditions varied from hot and sunny in summer to cold and icy in October. An individual appointment for the installation of the DAS was arranged for each participant. A technician mounted the DAS on the participants' bicycle and conducted a short cycling skill test with the participants in order to check their ability level (no specific deficits were observed). During installation, participants completed the pre-observation survey. Required maintenance procedures (DAS repairs, exchange of storage media) were carried out by trained technicians. After four weeks, the DAS was dismounted and participants completed the post-observation survey.

2.4 Data preparation

2.4.1 Video annotation

Before actual video annotation began, the material was checked for quality. In total, 85 videos had to be excluded from the analysis. Among these were recordings in which the bicycle was parked (*n* = 55) or in which the cyclists walked the bicycle (*n* = 10), i.e. no actual riding occurred. Only a small faction had to be excluded because of technical issues (*n* = 9) or because insufficient lighting during night time riding made annotation impossible (*n* = 11). To annotate the usable video material, we used ELAN (Wittenburg, Brugman, Russel, Klassmann, & Sloetjes, 2006), a free application provided by the Dutch Max Planck Institute for Psycholinguistics. The overall annotation procedure was based on Klauer, Perez, and McClafferty (2011). All annotators received a special training on the classification system used for annotation. Each annotation was double checked by a senior annotator. Any discrepancies were discussed and resolved in team meetings.

A three-step annotation procedure was developed to facilitate the analysis of SCEs and crashes. In the first step, videos were reviewed in order to identify potential events. As the identification of single bike events (apart from actual crashes) is very difficult and prone to error, we focused on SCEs which occurred during interactions with other road users. We classified such SCEs in accordance with Reynolds', Harris', Teschke's, Cripton's, and Winters' (2009) definition of a conflict as an “interaction between a bicyclist and another road user such that at least one of the parties has to change speed or direction to avoid a collision” (p. 4). Every potential SCE was reviewed and discussed with a group of annotators and the senior researcher before a decision was taken to include or not include it in the final set of events.

In the second step, the conflict partner (see Table 2 and the infrastructure the participant was travelling on (see Table 3) were annotated for each SCE. The classification of infrastructure was based on definitions found in German road traffic regulations (StVO). In the final step, a verbal description of the event was added to allow for a more vivid characterisation. This verbal description was standardised in a way that still allowed us to categorise situations based on the description. In total, 1,974 videos were reviewed and annotated in case an SCE was identified.

Table 2. Overview of annotated categories for conflict partners.

Conflict partner	Description
Pedestrian	
Bicycle	Bicycle, electric bicycle
Powered two wheeler	Motorbike, moped
Car	Car up to light commercial vehicle
Lorry	
Bus	
Rail transport	Train, tram
Other motorised vehicle	Mobility scooter, tractor
Multiple conflict partners	More than one type of road user, e.g. pedestrian with dog, or pedestrian and cyclist at the same time

Table 3. Overview of annotated categories for type of infrastructure.

Type of infrastructure	Description
Road	Regular road (shared with motorised vehicles), lane
Bicycle infrastructure	Bicycle lane, bike path
Pavement	
Pedestrian area	
Unpaved	Forest or field path
Miscellaneous	All other types of infrastructure, e.g. parking facility, small path between houses

An additional layer of video annotation was introduced to investigate infrastructure use in non-critical situations. For each participant, the infrastructure he/she was travelling on was annotated for each trip continuously. In total, 1,449 videos with a duration of about 383 hours were annotated. As the main goal of this annotation was to assess distance travelled on the different types of infrastructure, only trips for which usable speed sensor data were available were annotated - see 2.4.2.

2.4.2 Sensor data

In addition to the video data, we collected speed sensor data for each trip. The data of 28 participants were analysable (due to technical difficulties, data could not be obtained from three participants). Subsequently, speed and distance data were synchronised with the video annotations in our database. This made it possible to, for example, link infrastructure use (video) with travel distance (wheel sensor) to calculate the distance travelled on a specific type of infrastructure.

2.5 Data analysis

In order to assess SCEs for each of our three age groups, we analysed the time of day during which the SCE occurred, the conflict partners that were involved, the type of infrastructure on which the SCE took place, and the speed at which the cyclist was travelling immediately before the SCE. We also assessed the verbal description of the event, and used this qualitative information to determine the rate of traffic violations that occurred immediately before the SCE. A safety incident rate (SIR) (OECD/International Transport Forum, 2013) was calculated as the number of SCEs per 100km cycled for the different times of day and infrastructure types. Relative risk was calculated for select aspects by comparing two SIRs.

3 Results

Because of technical issues, video data were available for 31 participants and speed sensor data were only available for 28 participants. As we were mainly interested in the SCEs (which were identified through video review), we decided to keep all 31 datasets for analysis. In this results section, we always report the number of datasets (either N = 31 or N = 28) that were the basis for the analysis. In general, analyses that relied solely on the videos included 31 datasets. Any analysis that involved speed sensor data (speed, distance, time of day) used 28 datasets.

3.1 Mobility behaviour

Overall, our participants (N = 28) recorded 1,667 trips with a total distance of 5,280 kilometres and 372 hours of riding during the four weeks of data collection. On average, each participant cycled about 188.30 km during the study, with a mean trip distance per cyclist of 3.53 km (SD = 2.52 km). This translates into a mean of 13.30 hours (SD = 6.93) riding per cyclist overall, and a mean single trip duration of 15 min. It has to be noted that there were substantial differences in total distance covered (range 30.19 to 425.82 km) and total cycling duration (range 2.90 to 29.73 hours) between participants. Total mean speed was about 13.87 km/h (SD = 2.89), ranging from 9.03 km/h for the slowest and 20.15 km/h on average for the fastest participant.

The participants aged 41 to 64 years produced the highest average mileage (M = 210.86 km, SD = 113.26 km) and the longest overall riding time (M = 14.88 hours, SD = 8.27 hours). The older cyclists rode about 198.30 km / 14.42 hours each (SD = 131.38 km / 7.36 hours), the younger group 149.14 km / 9.98 hours (SD = 69.67 km / 3.45 hours). However, due to large in-group variance, there were no significant differences between the three age groups for either total mileage or total cycling duration. In terms of average speed, the older cyclists rode a little slower (M = 12.70 km/h, SD = 2.77 km/h) than the other two groups (41-64 years: M = 14.40 km/h, SD = 2.16 km/h, under 40 years: M = 14.90 km/h, SD = 3.50 km/h). However, again, there were no significant differences between the three age groups.

3.2 Safety critical events

A total of 77 SCEs (N = 31) were identified, an average of 2.48 events per participating cyclist (see Table 4 for an overview). Nearly 30% of the participants was not involved in any SCE. The majority (52%) experienced one to three events. Only six cyclists were involved in five or more SCEs. As Table 4 shows, there were hardly any differences between the age groups with regard to the number of SCEs. A Kruskal-Wallis-Test (data not normally distributed) confirmed this impression (H (2) = 0.654, p = .721, d = 0.18). In addition, we calculated the safety incident rate (SIR, Table 4). Again, we found no significant differences between the three age groups (H (2) = 0.481, p = .786, d = 0.32). However, it has to be acknowledged that test power was comparatively low (25%).

Table 4. Descriptive statistics for SCEs per age group (*N* = 31).

	Total	*M*	*SD*	*Median*	*Min*	*Max*	*SIR*
≤ 40 years	25	2.50	2.55	1.5	0	7	1.92
41-64 years	28	2.80	3.46	2.5	0	12	1.19
≥ 65 years	24	2.19	2.96	1.0	0	9	1.29
Total	**77**	**2.48**	**2.92**	**2.0**	**0**	**12**	**1.44**

For all age groups, the majority of the events occurred in the afternoon between 14:00 and 17:00 (*N* = 28). This roughly corresponds with the time at which most cycling took place (see Figure 1). In general, exposure and the relative frequency of SCEs appeared to be congruent (r_{all} = .931, $r_{\leq 40}$ = .828, $r_{41\text{-}64}$ = .882, $r_{\geq 65}$ = .908). However, even when corrected for exposure, the risk of an SCE appears to be highest in the afternoon hours (see Table 5). The analysis of SIRs for the different age groups and time of day segments also showed that SIR peaks for the younger and older cyclist groups in the morning between 8:00-10:59, with 1.75 (younger group) and 1.41 (older group) events per 100 km. For the younger group, this equals an increase in risk of about 50% compared to the time of day during which most cycling took place (afternoon).

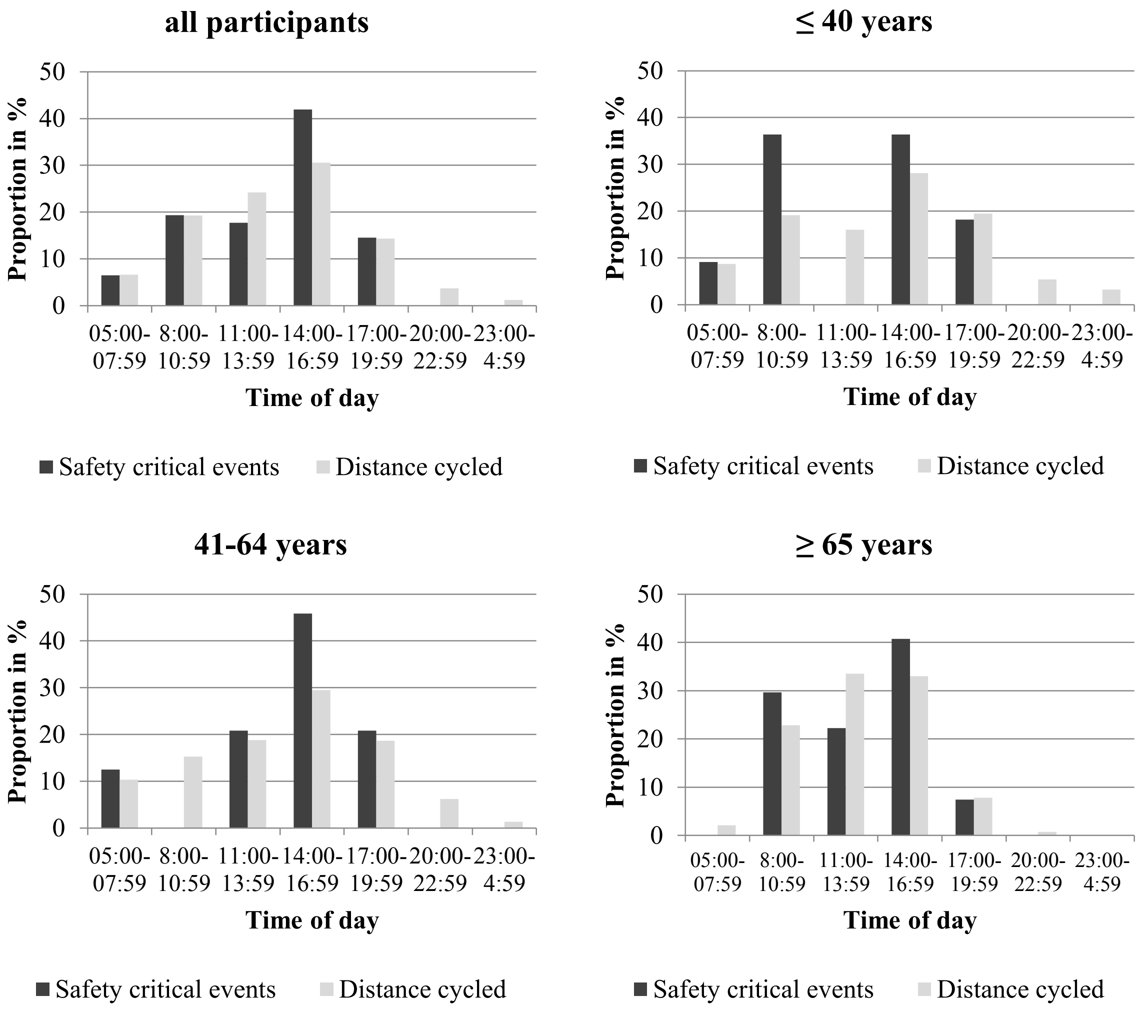

Figure 1. Proportion of SCEs and cycling distance for different times of day (*N* = 28).

Table 5. SIR dependent on time of day (*N* = 28).

	5:00-7:59	8:00-10:59	11:00-13:59	14:00-16:59	17:00-19:59	20:00-22:59	23:00 - 4:59
≤ 40 years	0.96	1.75	0.00	1.19	0.86	-	-
41-64 years	1.52	0.00	1.40	1.96	1.41	0.00	-
≥ 65 years	-	1.41	0.68	1.53	0.59	-	-
Total	**1.15**	**1.08**	**0.78**	**1.61**	**1.06**	**0.00**	**-**

Note. SIR only reported for cells with at least 100 trip kilometres.

In order to assess the potential effect of specific types of infrastructure on the occurrence of SCEs, we compared the amount of exposure to different infrastructure types to the relative frequency of SCEs across different types of infrastructure (N = 28). Table 6 displays the absolute mileage and the respective proportion of total mileage on each type of infrastructure, the number of SCEs and the SIR (for all age groups). Most of the time, participants were travelling on the road (i.e. in mixed traffic with motorised road users). For approximately one fourth of total trip distance, participants used bicycle-specific infrastructure (the younger cyclists used it somewhat less). Interestingly, about 10% of total trip distance was travelled on the pavement (14% in the youngest group), even though cycling on the pavement is in most cases illegal for adults in Germany.

When comparing infrastructure type exposure and relative frequency of SCEs, some clear discrepancies became apparent. While travelling on the road accounted for more than half of total trip distance, only about one third of the events occurred there. Another third of all SCEs was observed when participants used bicycle infrastructure, although this type of infrastructure was used for only one fourth of their distance. When comparing the SIR, the risk of an SCE on bicycle infrastructure was two times higher than on roads. This seems to be especially true for the two older groups, whereas the SIR was about the same for on-road cycling and cycling on bicycle infrastructure for cyclists of 40 years or younger. In general, it appears relatively safe to travel on unpaved roads and paths, with the risk of an SCE only 0.28-0.31 times the risk of an SCE on cycling infrastructure or the pavement. This is presumably because other road users are seldom encountered on unpaved roads. For our miscellaneous category (which included small paths between houses/in allotments or parking facilities), we found a comparatively high SIR. This might be explained by the fact that these types of infrastructure usually do not have (clear) rules and regulations. At the same time, it has to be acknowledged that these specific SCEs typically are low speed events.

Table 6. SCE, distance cycled and SIR on different types of infrastructure (*N* = 28).

Age groups	Infrastructure	Distance cycled (km)	Proportion of total distance cycled (in %)	Number of SCEs	Proportion of total number of SCEs (in %)	SIR
≤ 40 years	Road	612.7	60.7	8	50.0	1.31
	Bicycle infrastructure	184.6	18.3	2	12.5	1.08
	Pavement	142.9	14.2	4	25.0	2.80
	Pedestrian area	34.4	3.4	0	0.0	-
	Unpaved	13.7	1.4	2	12.5	-
	Miscellaneous	20.1	2.0	0	0.0	-
	Total	**1,008.4**	**100.0**	**16**	**100.0**	**1.59**
41-64 years	Road	800.2	48.2	6	24.0	0.75
	Bicycle infrastructure	467.6	28.2	14	56.0	2.99
	Pavement	161.2	9.7	3	12.0	1.86
	Pedestrian area	33.6	2.0	0	0.0	-
	Unpaved	146.8	8.9	0	0.0	0.00
	Miscellaneous	50.4	3.0	2	8.0	-
	Total	**1,659.8**	**100.0**	**25**	**100.0**	**1.51**

≥ 65 years	Road	1052.9	54.4	8	33.3	0.76
	Bicycle infrastruc-ture	465.3	24.0	7	29.2	1.51
	Pavement	175.5	9.1	4	16.7	2.28
	Pedestrian area	18.6	1.0	0	0.0	-
	Unpaved	155.2	8.0	0	0.0	-
	Miscella-neous	68.3	3.5	5	20.8	-
	Total	**1.935.8**	**100.0**	**24**	**100.0**	**1.40**
All participants	Road	2465.8	53.6	22	33.8	0.89
	Bicycle infrastruc-ture	1117.5	24.3	23	35.4	2.06
	Pavement	479.6	10.4	11	16.9	2.29
	Pedestrian area	86.6	1.9	-	-	-
	Unpaved	315.7	6.9	2	3.1	0.63
	Miscella-neous	138.8	3.0	7	10.8	5.04
	Total	**4604.0**	**100.0**	**65**	**100.0**	**1.41**

Note. SIR only reported for cells with at least 100 trip kilometres.

An overview of the SCE conflict partners and the infrastructure used when the SCE occurred ($N = 31$) is given in Table 7. The most frequent conflict partners were cars, followed by pedestrians and other cyclists. This pattern was more or less identical for all three age groups (see Appendix Table A1). As could be expected, the majority of car-bicycle conflicts occurred when the participants were using the road for cycling. Likewise, most bicycle-bicycle conflicts were observed on cycling infrastructure. The pattern was less clear for conflicts involving pedestrians and multiple road users (mostly pedestrians with dogs).

Table 7. Number of SCEs per type of infrastructure and conflict partner (*N* = 31).

Conflict partner	Road	Bicycle infra-structure	Pavement	Pedestrian area	Unpaved	Miscellaneous	**Total**
Car	20	4	3	0	0	3	**30**
Bicycle	3	9	2	2	0	0	**16**
Pedestrian	3	5	8	0	2	4	**22**
Lorry	1	0	0	0	0	0	**1**
Bus	0	1	0	0	0	0	**1**
Other motorised vehicle	0	1	0	0	0	0	**1**
Multiple conflict partners	0	5	0	0	0	1	**6**
Total	**27**	**25**	**13**	**2**	**2**	**8**	**77**

Note. Only categories with at least one SCE are reported in this table.

There were substantial differences in the type of situations observed in conflicts with motorised road users, other cyclists and pedestrians (*N* = 31, see Table 8). SCEs with motorised vehicles were frequently caused by drivers failing to yield the right of way to the cyclist. A typical situation was a motorised vehicle turning right and crossing the bike path (apparently) without checking for cyclists. Another common error was observed at intersections, at which the motorised vehicle failed to yield to the cyclist who was approaching from the right. In addition, several SCEs were caused by parking and turning manoeuvres.

In interactions with other cyclists, many situations were characterised by sudden and presumably unexpected manoeuvres of the other cyclist. Conflicts also arose as a result of passing or being passed closely either in the same (overtaking) or opposite direction. Similar situations occurred with pedestrians, although the event category that occurred most frequently was the crossing situation, e.g. a pedestrian on the pavement that crossed the road or the cycle path in order to get to the other side of the road.

Table 8 further breaks down the situation classification by the three different age groups. While descriptively, some peaks for certain groups and situations (e.g. conflicts with parking and turning vehicles mostly for younger cyclists) are visually indentifiable, the cell sizes are too small to justify a detailed comparison.

Table 8. SCEs in detail (*N* = 31).

	Number of SCE			
Description of the SCE	≤ 40 years	41-64 years	≥ 65 years	**Total**
Conflict with motorised vehicle				
Trajectories of motorised vehicle and participant crossed				
Motorised vehicle failed to yield to participant	2	4	3	**9**
Participant failed to yield to motorised vehicle	2	1	1	**4**
Parking or turning manoeuvre of motorised vehicle. entering path of participant	5	1	1	**7**
Motorised vehicle and participant travelled in the same direction				
Motorised vehicle closely passed participant	1	2	1	**4**
Participant tried to pass stopped/slow motorised vehicle too closely (passing attempt aborted)	2	0	0	**2**
Motorised vehicle swerved or suddenly stopped in front of participant	1	0	1	**2**
Motorised vehicle and participant travelled in opposite directions				
Motorised vehicle passed another vehicle using path of oncoming participant	0	2	1	**3**

Conflict with cyclist(s)				
Trajectories of cyclist(s) and participant crossed, other cyclist(s) unexpectedly crossed path of participant	1	1	1	**3**
Cyclist(s) and participant travelled in the same direction, sudden braking or swerving by other cyclist(s) in front of participant	1	5	2	**8**
Cyclist(s) and participant travelled in opposite directions, irritation about how to go about passing each other	3	1	2	**6**
Conflict with pedestrian(s)				
Trajectories of pedestrian(s) and participant crossed, pedestrian(s) crossed path of participant (e.g. jaywalking)	4	2	6	**12**
Pedestrian(s) and participant travelled in the same direction, pedestrian(s) suddenly stopped or moved into path in front of participant	2	2	0	**4**
Pedestrian(s) and participant travelled opposite directions, oncoming pedestrian(s) entered path of participant unexpectedly	1	5	2	**8**
Conflicts with dogs (unexpectedly entering path of participant)	0	2	3	**5**

We also investigated obvious traffic violations in SCEs (see Table 9). In more than half of the SCEs, no obvious violation by our participant or the conflict partner was observed. In seven cases, neither of the two conflict partners fully complied with the road rules. The number of participant violations were similar for each age group ($n_{\leq 40}$ = 8, $n_{41\text{-}64}$ = 7, $n_{\geq 65}$ = 7). A detailed description of the nature of the violations is displayed in Table 10. The most common participant violation in observed SCEs was the use of the wrong infrastructure, e.g. pavement instead of road. Consequently, such SCEs mostly involved pedestrians. We also observed several SCEs in which our participants cycled against the direction of traffic (on cycling infrastructure). The most common violation of conflict partners in SCEs was the failure to yield, usually by motorised vehicles.

Table 9. Participant and conflict partner violations immediately before the SCE (*N* = 31).

		Behaviour of conflict partner		
		No violation	Violation	**Total**
Participant behaviour	No violation	42	13	**55**
	Violation	15	7	**22**
	Total	**57**	**20**	**77**

Table 10. Participant and conflict partner violations immediately before the SCE in detail (*N* = 31).

Violations in detail	Participant	Conflict Partner
Wrong type of infrastructure	13	3
Failure to yield	4	9
Cycling against direction of traffic	6	2
Overtaking on the wrong side	2	0
Moving out of parking space without signal	0	4
Opening the door	0	1
Changing into a participant's lane in a way that forces the participant to take evasive action (e.g., brake, dodge) [referred to as Nötigung in Germany]	0	2

Note. Multiple violations could occur at the same time.

While the relatively low logging frequency (2Hz) did not allow for the creation of meaningful speed profiles in the SCEs, we used speed data to describe the conditions that preceded the event (*N* = 28). We calculated mean speed over a period of 10s directly preceding the SCE. This was compared to the distance travelled at this speed (Figure2). It is important to note the difference between the two distributions. While there is a clear peak between 15 and 20 km/h for the distance cycled (with an apparently normal distribution around this peak), a visual assessment of the SCE distribution indicates a shift towards lower speeds. This appears to be true (with minor variations) for all three age groups.

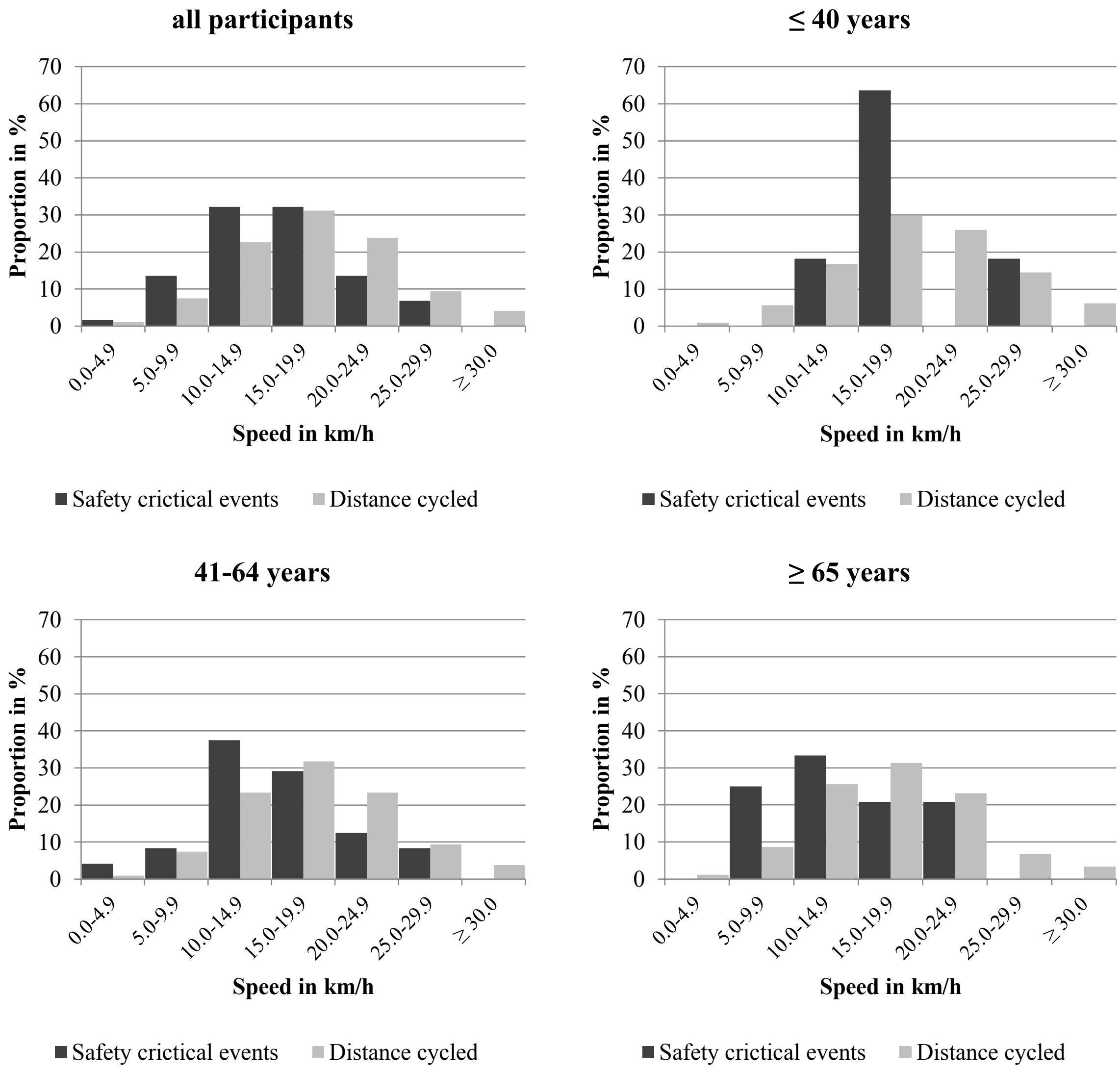

Figure 2. Proportion of SCEs and distance cycled at different speeds (N = 28).

4 Discussion and Conclusions

The aim of the study was to investigate SCEs in cycling using a naturalistic cycling methodology. We were able to identify 77 events in about 400 hours of cycling. We found no differences between our different age groups with regard to the relative frequency of SCEs, which suggests that older cyclists are not more at risk than younger cyclists are. However, it has to be acknowledged that the consequences of a crash are usually more severe for older cyclists (e.g. Boufous et al., 2012; Rodgers, 1997; Statistisches Bundesamt [Destatis], 2013). Kaplan, Vavatsoulas, and Prato (2014) claim that compared to younger people, cyclists over 60 years old are at a much greater risk of sustaining severe injuries.

Clear differences were observed between data on conflict partners in our dataset and analogous data found in accident statistics (Statistisches Bundesamt, 2011). Although cars were still the most frequent conflict partner, the proportion of incidents involving motorised vehicles was only slightly above 40%, while SCEs with pedestrians and other cyclists combined accounted for 57% of all incidents. This finding is in line with the results of the NCS of Dozza and Werneke (2014). Proportions found in travel diary data (de Geus et al., 2012) differ slightly, however not fundamentally, as collisions with cars were reported as causes of a crash about as often (11.4% of all cases) as collisions with pedestrians (5.7%) or cyclists (4.3%) combined. The proportions found in hospital data strongly depend on the level of severity that is analysed. When looking into hospitalisations only, the proportion of crashes involving motorised vehicles is much higher (Short & Caulfield, 2014). Data from patients who were admitted to an emergency care unit indicate a proportion of 4:1 between crashes involving motorised vehicles and crashes involving other cyclists (Juhra et al., 2012). Ellwein (2011) reported a proportion of about 2.5:1 between cars and cyclists.

When examining SCEs across different types of infrastructure, it became apparent that the risk of SCEs on designated cycling infrastructure per distance travelled was relatively high. In contrast, the risk of an SCE on the road per distance travelled was rather low. It has to be noted that in travel diaries (de Geus et al., 2012) and data collected at crash scenes (Richter et al., 2007), the proportion of crashes that occurred on the road was close to 70%. However, these studies were not able to control for exposure, so it is unclear how this relatively high number relates to actual risk. Still, the fact that the conflict partner in our road incidents was most often a motorised vehicle implies that the consequences of a crash on the road would also be more severe (Kaplan et al., 2014; Walter, Achermann Stürmer, Scaramuzza, Niemann, & Cavegn, 2012).

In general, it is important to note that less than a half of the identified events involved other motorised vehicles or occurred on-road. This clearly indicates that the sole focus on on-road, bicycle-motor vehicle conflicts found in official statistics, as well as a considerable part of the available research, is not justified. It also cannot be argued that such incidents are negligible. Twisk and Reurings (2013) point out that under daylight conditions, cycling collisions that do not involve motorised vehicles (mostly single vehicle incidents) account for twice as many injuries as collisions with motorised vehicles. Others have reported similar results (de Geus et al., 2012; Tin Tin, Woodward, & Ameratunga, 2010). The high proportion of hospital admissions as a result of collisions not involving motorised vehicles (Stutts, Williamson, Whitley, & Sheldon, 1990) provides evidence that such crashes are a significant health issue and an economic burden (Veisten et al., 2007). The results of Juhra et al., (2012) also showed that there are differences in the types of injuries that are caused by bicycle-motor vehicle collisions and other crashes involving bicycles. Whereas traumatic brain injury was the most frequent type of injury resulting from a collision with a motorised vehicle, fractures of the upper extremities were the most common injury in all other types of crashes. This is further evidence that an approach, which includes not only motorised vehicles as conflict partners, but also non-motorised road users and single vehicle crashes, is required.

It has to be acknowledged that the overall number of incidents in our dataset was rather small. With only a few events observed in certain event categories (e.g. conflicts with lorries), the conclusions that can be drawn are somewhat limited in their validity. It is therefore advisable to collect naturalistic cycling data on a larger scale, in order to observe a larger number of crashes and incidents. Similar to how the 100 car study (Dingus et al., 2006) can be seen as the precursor to the much larger SHRP2 (Campbell, 2013), the study presented in this paper might be considered an important, but not final step in the application of the naturalistic driving methodology to cycling. Given this function, the study has provided evidence that NCS are a feasible, albeit laborious, approach to investigating cycling collisions and safety critical incidents.

In order to conduct NCS on a larger scale, further methodological and technical improvements are necessary. On the technical side, the need for participants to manually start and stop recording interferes to some degree with naturalistic data collection, as participants are frequently reminded that they are being observed. The development of an automatic start/stop mechanism that can be installed on participants' bicycles (see Dozza and Werneke (2014) for an example of such a mechanism on a test bike) appears to be an important step. While battery life has improved considerably relative to previous studies, battery life must improve further in order to deploy data acquisition systems on a large scale, as the close care that we were able to provide for our participants is not feasible in larger samples. Additional improvements of the system that might contribute to a richer dataset include better night vision cameras, a wider view of the scenery and the cyclist, as well as an accelerometer.

Additional developments in terms of methodology are also required in order to advance understanding of cycling safety. In particular, the definitions of SCE and criticality are problematic aspects of NCS, as they are even less straightforward than in NDS. The fact that cyclists use a variety of different infrastructures and subsequently encounter potential conflict partners in situations very different from on-road driving makes the development of clear definitions very difficult. For example, situations that would be considered dangerous in (motor-) vehicle-pedestrian interactions (e.g. passing closely) are, intuitively, somewhat more difficult to characterise as SCEs in bicycle-pedestrian interactions.

However, with due acknowledgment of methodological and technological limitations, a major strength of our study is that it allowed for the identification of various SCEs in cycling and advanced understanding of the circumstances under which such events occur. NCS as a method can provide insight into a variety of aspects of cyclist behaviour, including not only accidents and SCEs, but also infrastructure usage and mobility behaviour. Future NCS are expected to help answer a wide range of theoretical and practical questions concerning traffic psychology, urban planning and traffic engineering.

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Appendix

Table A1. Number of SCEs per type of infrastructure and conflict partner per age group (*N* = 31).

≤ 40 years	Infrastructure						
Conflict partner	Road	Bicycle infra-structure	Pavement	Pedestrian area	Unpaved	Miscellaneous	**Total**
Car	6	1	3	0	0	1	**11**
Bicycle	2	0	1	1	0	0	**4**
Pedestrian	3	1	1	0	2	0	**7**
Lorry	1	0	0	0	0	0	**1**
Bus	0	1	0	0	0	0	**1**
Other motorised vehicle	0	0	0	0	0	0	**0**
Multiple conflict partners	0	1	0	0	0	0	**1**
Total	**12**	**4**	**5**	**1**	**2**	**1**	**25**

41 – 64 years	Infrastructure						
Conflict partner	Road	Bicycle infra-structure	Pavement	Pedestrian area	Unpaved	Miscellaneous	**Total**
Car	7	2	0	0	0	1	**10**
Bicycle	0	7	0	1	0	0	**8**
Pedestrian	0	3	3	0	0	1	**7**
Lorry	0	0	0	0	0	0	**0**
Bus	0	0	0	0	0	0	**0**
Other motorised vehicle	0	1	0	0	0	0	**1**
Multiple conflict partners	0	1	1	0	0	0	**2**
Total	**7**	**14**	**4**	**1**	**0**	**2**	**28**

≥ 65 years	Infrastructure						
Conflict partner	Road	Bicycle infra-structure	Pavement	Pedestrian area	Unpaved	Miscellaneous	**Total**
Car	6	1	0	0	0	1	**8**
Bicycle	1	2	1	0	0	0	**4**
Pedestrian	0	1	3	0	0	3	**7**
Lorry	0	0	0	0	0	0	**0**
Bus	0	0	0	0	0	0	**0**
Other motorised vehicle	0	0	0	0	0	0	**0**
Multiple conflict partners	1	3	0	0	0	1	**5**
Total	**8**	**7**	**4**	**0**	**0**	**5**	**24**

PAPER III

DRIVERS' GAP ACCEPTANCE IN FRONT OF APPROACHING BICYCLES – EFFECTS OF BICYCLE SPEED AND BICYCLE TYPE

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DRIVERS' GAP ACCEPTANCE IN FRONT OF APPROACHING BICYCLES - EFFECTS OF BICYCLE SPEED AND BICYCLE TYPE

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Abstract

The growing popularity of electric bicycles gives rise to a variety of road safety questions. One of the issues is e-bikes' potential to achieve a higher speed compared to conventional bicycles. Especially for road users that are unfamiliar with that type of bicycle, underestimations of speed might be suspected which could lead drivers to accept unsafe gaps (e.g. for turning manoeuvres) in front of approaching e-bikes. But also higher speed as such might prove problematic, as previous studies have shown repeatedly that drivers tend to choose smaller time gaps in front of vehicles approaching at higher speed. Forty-two drivers (two age groups) were recruited to investigate their gap acceptance behaviour on a test track. Participants were seated in a car, waiting to enter traffic, which would have required crossing a lane on which a cyclist approached. Cyclists approached at speeds between 15 and 35 km/h and rode either a conventional bicycle or an e-bike. Participants were instructed to press a foot pedal to indicate the last moment at which they would be willing to enter traffic in front of the bicyclist. Results show that with increasing cyclist speed, accepted time gaps became significantly shorter. At the same time, participants appeared to select shorter time gaps when the approaching bicycle was an electric one, even though the two different bicycle types could not be distinguished from the participants' position. Although we found only few accepted gap sizes that would have been especially risky, the findings indicate that the effect of bicycle speed has to be considered when discussing the consequences of an increased e-bike prevalence for road safety.

Keywords: road safety, e-bike, time to arrival

1 Introduction

Electric bicycles have seen a steep rise in popularity in the last decade (Rose, 2012). Sales figures in Germany (Zweirad-Industrie-Verband, 2013) and other European nations are growing, and are expected to continue to grow (Zweirad-Industrie-Verband, 2011). In China, e-bike sales figures reached 10 million per year already in 2005 (Weinert, Ma, Yang, & Cherry, 2007). In general, this development is welcomed, as cycling, also on e-bikes, is considered a healthy, environmentally friendly mode of transport. Previous studies also indicate that a lot of e-bike users do not necessarily use it as a substitute for a conventional bike, as it has been reported that the length of trips made with an e-bike was considerably longer (Cherry & Cervero, 2007). It appears that the e-bike is often a substitute for public transport (An, Chen, Xin, Lin, & Wei, 2013) or a car (Popovich et al., 2014). In addition, a lot of elderly cyclists that would otherwise not be able to ride a conventional bike because of their physical condition can continue to cycle (Dill & Rose, 2012; Parker, 2006). It has been found that even elder citizens that gave up cycling previously are getting back onto the road on e-bikes (Alrutz, 2013). In terms of promoting healthy and environmentally friendly mobility, the trend towards e-bikes might be embraced unequivocally.

However, as more and more e-bikes are on the road today, road safety concerns have been voiced. Chinese accident statistics (Feng et al., 2010) show that the rate of crashes that involve e-bikes has risen continuously in recent years (however, it has to be acknowledged that the Chinese definition of e-bike is much wider than the European one). Data from Switzerland, where e-bikes are listed as a separate category of road user in the accident statistics since 2011, point in a similar direction (Achermann Stuermer et al., 2013). Especially worrisome is the fact that accident severity appears to be higher than for conventional bicycles.

In this context, one aspect that has been questioned is how other road users cope with the fact that there now is something on the road that looks like a normal bicycle, however accelerates much faster, and reaches quite different speed levels than a conventional bicycle. In a German survey of e-bike riders, one of the potentially hazardous situations that the cyclists considered relevant was the underestimation of their speed by a motorised vehicle (Alrutz, 2013). Schleinitz, Petzoldt, Franke-Bartholdt, Krems and Gehlert (2014) showed that e-bikes reach higher mean speeds, and also travel for longer proportions of their trips at speeds beyond 20, 25 and 30 km/h. Similar results have been reported by others (Cherry & He, 2009; Hacke, 2013).

It has been found previously that vehicle approach speed influences drivers’ gap acceptance behaviour. Already in 1977, turning manoeuvres at a T-junction were observed in order to gain insight into the effect of speed on gap acceptance (Cooper, Storr, & Wennell, 1977). The analysis showed an effect of speed (which varied between 27.5 mi/h and 42.5 mi/h - i.e. 44.2 km/h and 76.5 km/h) on the size of accepted time gaps, with smaller gaps being accepted with increasing speed. Alexander, Barham and Black (2002) let participants drive in a driving simulator and required them to complete right turn manoeuvres (be aware that this study is from the UK, i.e. the situation equals a left turn manoeuvre in most other countries). Participants were instructed to stop at the intersection, and make a turn across a lane with oncoming traffic when they considered it safe to do so. The oncoming cars approached at either 30 mi/h (approximately 48.3 km/h) or 60 mi/h (approximately 96.6 km/h). The results showed that drivers tended to accept gaps that were on average 2 s smaller when the approaching vehicle was travelling faster. Similar results have been reported from another driving simulator study Yan, Radwan and Guo (2007), in which participants were required to turn left (in a right hand driving environment) into the traffic stream. Here, the accepted gaps at the higher speed level were about 1.6 s smaller than the ones accepted at lower speed. The tendency to accept smaller gaps when the approaching vehicle is faster appears to be relatively stable, and has been found also for pedestrian crossing decisions (Lobjois & Cavallo, 2007; Oxley, Ihsen, Fildes, Charlton, & Day, 2005; Petzoldt, 2014).

In addition to vehicle approach speed, a number of other aspects have been reported to influence the size of the accepted gaps, such as the type of the oncoming vehicle (Bottom & Ashworth, 1978) or the observing drivers' gender (Alexander et al., 2002; Yan et al., 2007). One central factor is drivers' age. A common finding is that younger drivers tend to accept smaller gaps than older motorists (Alexander et al., 2002; Yan et al., 2007). Interestingly, the effect of speed is often more pronounced in older drivers, i.e. the size of the accepted gaps differs much more between different speed levels (Yan et al., 2007). One potential explanation that has been provided for this interaction between age and approach speed is that older drivers appear to "overestimate at lower speeds and underestimate at higher speeds" (Scialfa, Guzy, Leibowitz, Garvey, & Tyrrell, 1991).

Most of the effects described above are a direct reflection of effects found for time to collision (TTC) / time to arrival (TTA) judgments. The estimation of the time it takes an object to arrive at a certain predefined position is often argued to underlie road users' decisions and behaviour (Rock & Harris, 2006; Stewart, Cudworth, & Lishman, 1993). Probably the most prominent theoretical assumption on how such an estimation is made is the so called tau-hypothesis (Lee, 1976). Following this hypothesis, the perception of TTC is direct and does not require additional processing of, e.g., object size or distance. However, since "tau-theory has become one of the best researched topics in perceptual psychology" (Hecht & Savelsbergh, 2004), it has become clear that there is more to TTC estimation than just the observation of optical expansion.

One of the most replicated findings is that there is a positive correlation between object approach speed and participants' TTC estimates (Hancock & Manser, 1997; Manser & Hancock, 1996; Oberfeld & Hecht, 2008; Schiff, Oldak, & Shah, 1992; Schiff & Oldak, 1990). The explanation provided for this effect is that, to some degree, observers rely on physical distance to make estimates of TTC, a phenomenon that has been described as distance bias (Law et al., 1993). Petzoldt (2014) was able to show that the effect of approach speed on the gap size accepted by pedestrians can be explained mainly with this effect.

Age effects have been found for judgments of TTC, too. Usually, it is reported that older observers are less accurate than younger ones in estimating TTC. What this phrasing of the findings fails to acknowledge is that in most cases, this lower accuracy is actually a systematic bias towards lower estimates, i.e. older observers show a strong tendency to underestimate TTC (Hancock & Manser, 1997; Petzoldt, 2014; Schiff et al., 1992). This, at least partially, can serve as an explanation for the differences in accepted gap size between different age groups.

Unfortunately, (applied) TTC studies and gap acceptance studies alike mostly focused solely on situations in which judgments or decisions in relation to motorised vehicles were required. The vehicle approach speeds investigated were usually 40 km/h or higher. One exception is te Velde's, van der Kamp's, Barela's and Savelsbergh's (2005) study of pedestrian crossing behaviour when confronted with an oncoming bicycle (however, with a maximum speed of just 6.5 km/h). If the effect of speed on accepted gap size can also be found at speed levels that are typical for bicycles is, at this stage, unclear. Also, the differences between the investigated speed levels were often rather high, leaving open the question of whether rather subtle differences in speed, as they would be expected between conventional bicycles and e-bikes, would be perceived and acted upon.

Aim of the experiment presented in this paper was to investigate what gap sizes drivers choose when confronted with an oncoming cyclist. The experiment was conducted on a test track, where participants seated in a car were supposed to indicate their minimum acceptable gap when asked to turn in front of an approaching bicycle.

Of primary interest was the effect of the cyclist's speed on the accepted gaps, and whether it matters if the approaching vehicle is a conventional bicycle or an e-bike. Based on the reported findings, we hypothesised that a higher approach speed would result in smaller accepted time gaps. The inclusion of bicycle type was of explorative character. Given that vehicle-related differences in gap acceptance have usually been linked only to vehicle size, we did not expect to find differences between conventional bicycles and e-bikes.

In addition, we manipulated the road gradient and the observers' perspective. Gradient appeared to be an interesting factor as the use of an e-bike allows its user to achieve speed levels when riding uphill which, with a conventional bicycle, are usually only achieved on flat sections of road. As common sense suggests, and data from Schleinitz et al. (2014) show, cyclists are slower when riding uphill compared to their average cycling speed. If drivers use this knowledge for their gap acceptance decisions, they should be more willing to turn in front of a bicycle that is approaching uphill, i.e., we should expect smaller accepted gaps under this condition.

With regard to the observers' perspective, we assumed that a side view might allow for a somewhat better estimate of the approaching cyclists speed. It has been suggested that a certain degree of eccentricity when observing an oncoming object would lead to better judgments of its approach (Schiff & Oldak, 1990). A side view might provide sufficient eccentricity, whereas a frontal view would certainly not. However, it was not clear what effect such a better judgment of approach would have on gap acceptance, so we did not formulate a specific hypothesis.

Finally, to account for the widely reported age effects, we investigated two different age groups. We expected younger drivers to accept smaller gaps than older ones. (Table 1 gives an overview of the different factors and factor levels of the experiment.)

2 Method

2.1 Participants

Forty-two participants in two age groups (30-45 years, 65 years and older) took part in the experiment. The younger group (13 male, 8 female) had a mean age of 34.0 years (*SD* = 4.4), the older participants (18 male, 3 female) were, on average, 71.1 years (*SD* = 5.0) old. All participants had a driver's license. Their reported annual mileage was approximately 16,000 km (younger group) and approximately 13,500 km (older group), respectively.

2.2 Experimental conditions (see Table 1 for an overview)

We used two different bicycles in the study, a conventional bike and an e-bike (see Figure 1). The electric bicycle provided pedalling support up to 45 km/h. Rear-view mirror and license plate (both required for fast e-bikes in Germany) were removed to make the e-bike look like an ordinary bicycle. The conventional bicycle was chosen to resemble the looks of the e-bike as closely as possible, so that there were no obvious differences in design that could be spotted from a distance. Both bicycles had a small cycling computer installed to display the current speed.

Figure 1. Conventional bicycle (left) and e-bike (right) used in the experiment.

To manipulate road gradient, we conducted the experiment on two different "tracks". One track had practically no gradient at all, so bicycles were approaching on a more or less flat section of road. The other track had a grade of 3.75 %, resulting in a slight uphill climb for the cyclists.

Two different situations in which the car would have crossed the path of the approaching bicycle were implemented (Figure 2), resulting in two different perspectives for the observer. In the first situation, the car was supposed to turn left in front of a bicycle approaching from the opposite direction, so the driver had a frontal view of the cyclist (Figure 2, left). A left turn manoeuvre was also the basis for the second situation, however, here, the bicycle was approaching from the left (and had, per instruction, the right of way), which resulted somewhat more in a side view of the oncoming cyclist (Figure 2, right).

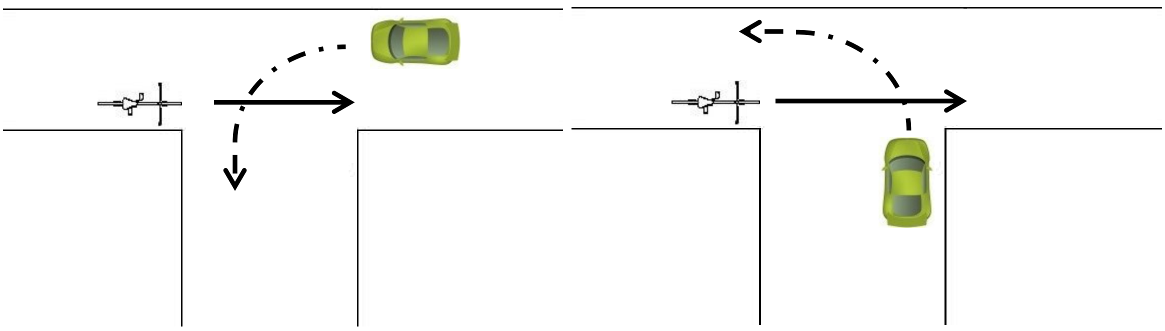

Figure 2. Experimental setup for frontal view (left) and side view (right) of the approaching bicycle (participant seated in vehicle).

We selected four different speed levels. Speeds of 15, 20 and 25 km/h were used for both bicycle types. In addition, a 35 km/h condition was realised with the e-bike (within the experimental setup, this speed could not be achieved with the conventional bicycle). The bicycles were ridden by student assistants that we trained previously, so they would be able to reach and hold the required speed. The cyclists used the display of the cycling computer to observe their own speed. If a deviation of more than 1 km/h (as displayed) in the crucial phase of the approach occurred, the trial was aborted and repeated.

With the exception of the 35 km/h condition, all within-factor levels were fully crossed. This resulted in a total of 28 different combinations (2x2x3 with the conventional bike plus 2x2x4 with the e-bike). Both age groups were confronted with all 28 combinations.

Table 1. Overview of factors and factor levels.

age	bicycle type	road gradient	observer's perspective	speed
30-45	conventional bike	0%	front view	15 km/h
65 +	e-bike	3.75%	side view	20 km/h
				25 km/h
				35 km/h (e-bike only)

2.3 Procedure

Before the actual experiment began, we conducted a vision test (Snellen eye chart) to ensure that participants would be able to perceive the approaching bicycle correctly. None of the participants showed substantial vision impairments, with 39 out of 42 having a visual acuity of 100% or above for at least one eye (the remaining three had a minimum of 67% visual acuity). This was followed by the collection of demographic data. Then, the actual experiment began.

Participants were seated in a real car to observe the approaching cyclists from a driver's perspective. A foot pedal was installed that should be pressed to indicate a turning/crossing decision. A camera was positioned outside the vehicle to record the cyclist's approach. In front of the camera, a small LED was installed that lit up when the foot pedal was depressed. This setup allowed us to link the participants' response to the position and speed of the approaching bicycle.

Once seated, participants received the necessary instructions. At the beginning of each trial, they were supposed to hold their head in a position that did not allow them to look outside the car when the cyclist's approach started. When the cyclist reached a distance of about 100 m from the car, the experimenter gave a signal that it was now allowed to observe the cyclist approaching. Participants then depressed the foot pedal when they considered the cyclist to be in a distance that would be their minimum acceptable gap to still cross in front of the cyclist. They were instructed to choose a gap which they felt would still be comfortable and safe in a "normal" drive, i.e. not being in a hurry, but also not being exceptionally relaxed. Participants completed two practice trials before data acquisition started.

As the manipulation of road gradient (0% vs. 3.75%) and observer's perspective (front view vs. side view) required different setups on the test track, we had four different experimental blocks that were balanced across all participants. Inside these blocks, e-bike and conventional bike approach alternated (we had two student assistants, dressed identically, one on each bike, who took turns at the task to speed up the process and prevent fatigue). The order of the different speed levels was randomized (see Table 2 for an example of how the experimental blocks were arranged). After the experimental trials were completed, participants were debriefed and received their monetary compensation of €25. In total, the complete experiment took about 90 min.

Table 2. Example of experimental block arrangement.

Trial Number	Block 1 0% / front view	Block 2 3.75% / front view	Block 3 3.75% / side view	Block 4 0% / side view
1	e-bike / 25 km/h	e-bike / 15 km/h	e-bike / 35 km/h	e-bike / 15 km/h
2	bike / 15 km/h	bike / 20 km/h	bike / 15 km/h	bike / 15 km/h
3	e-bike / 35 km/h	e-bike / 25 km/h	e-bike / 20 km/h	e-bike / 25 km/h
4	bike / 20 km/h	bike / 15 km/h	bike / 25 km/h	bike / 20 km/h
5	e-bike / 15 km/h	e-bike / 35 km/h	e-bike / 15 km/h	e-bike / 20 km/h
6	bike / 25 km/h	bike / 25 km/h	bike / 20 km/h	bike / 25 km/h
7	e-bike / 20 km/h	e-bike / 20 km/h	e-bike / 25 km/h	e-bike / 35 km/h

To have a certain benchmark of how long it would have taken to actually cross/turn in front of the cyclist, we asked two individuals to complete the crossing/turning manoeuvre several times with their personal vehicles. This was done after the experiment, with no other road users present, and no specific instructions (other than to complete a "normal" turning manoeuvre). We measured the time it took from standstill until the vehicle had crossed the lane and was positioned in a 90° angle (i.e. in driving direction) again. We considered the result to be the critical gap size for the implemented scenario. It has to be acknowledged that this procedure was rather unstandardized, and allows only for a coarse estimation of actual crossing/turning time (e.g., reaction times / latencies of driver and vehicle are not included).

3 Results

We analysed the data in a five factorial ANOVA for mixed designs, omitting the 35 km/h condition (which was missing for the conventional bicycles). This condition, however, is still included in the figures for visual comparison. An overview of the ANOVA and corresponding effect sizes, including main effects and interactions, can be found in Table 2.

In Figure 3, the size of the accepted gaps dependent on the approaching cyclist's speed is displayed. As can be clearly seen, participants tended to accept smaller gaps when the approach speed was higher, which was confirmed through statistical analysis, F (2, 80) = 68.95, p < 0.001, η^2_p = .63. Post-hoc comparisons (Bonferroni-corrected for multiple comparisons) showed significant differences between all three analysed speed levels (all p < .001). It has to be noted that although the vast majority of accepted gaps would have been safe, we found 29 accepted gaps (out of 1,176, approximately 2.5%) that were smaller than the critical gap size of 3.4 s.

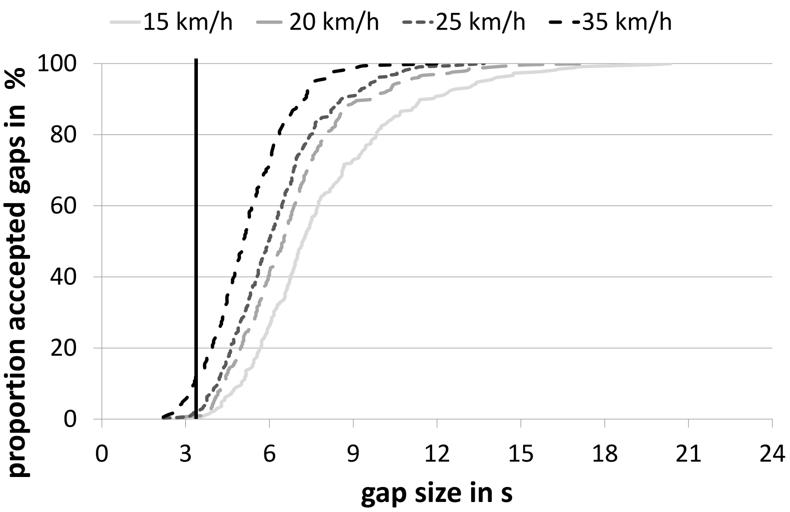

Figure 3. Cumulative proportion of accepted gaps of a certain size for crossing/turning dependent on the cyclist's approach speed. Solid vertical line indicates critical gap size of 3.4 s.

Figure 4 displays the accepted gap size for the different speed levels depending on the four factors bicycle type, road gradient, observer's perspective and observer's age. A clear effect was found for the comparison of the two bicycle types (Figure 4, top left). The size of the accepted gaps was consistently about 0.5 s smaller when participants were approached by an electric bicycle as compared to a conventional bicycle, F (1, 40) = 18.41, p < 0.001, η^2_p = .32.

Likewise, the road's gradient had an influence on the size of the accepted gaps (Figure 4, top right). When the approaching cyclist was riding uphill, accepted gaps were again about 0.5 s smaller then when there was no grade, F (1, 40) = 12.21, p = 0.001, η^2_p = .24. The observers' perspective (Figure 4, bottom left) did not appear to affect accepted gap size, F (1, 40) = 0.61, p = 0.438, η^2_p = .02.

From the inspection of the mean values, it appears that participants' age played a role in the size of accepted gaps as well, with differences of up to 1.0 s between the two age groups for certain speed levels (Figure 4, bottom right). However, the ANOVA showed no main effect of age group, F (1, 40) = 1.02, p = 0.319, η^2_p = .03. It has to be acknowledged that an effect size of about η^2_p = .1 would have been required to find a significant difference between the two age groups (with a statistical power of .8).

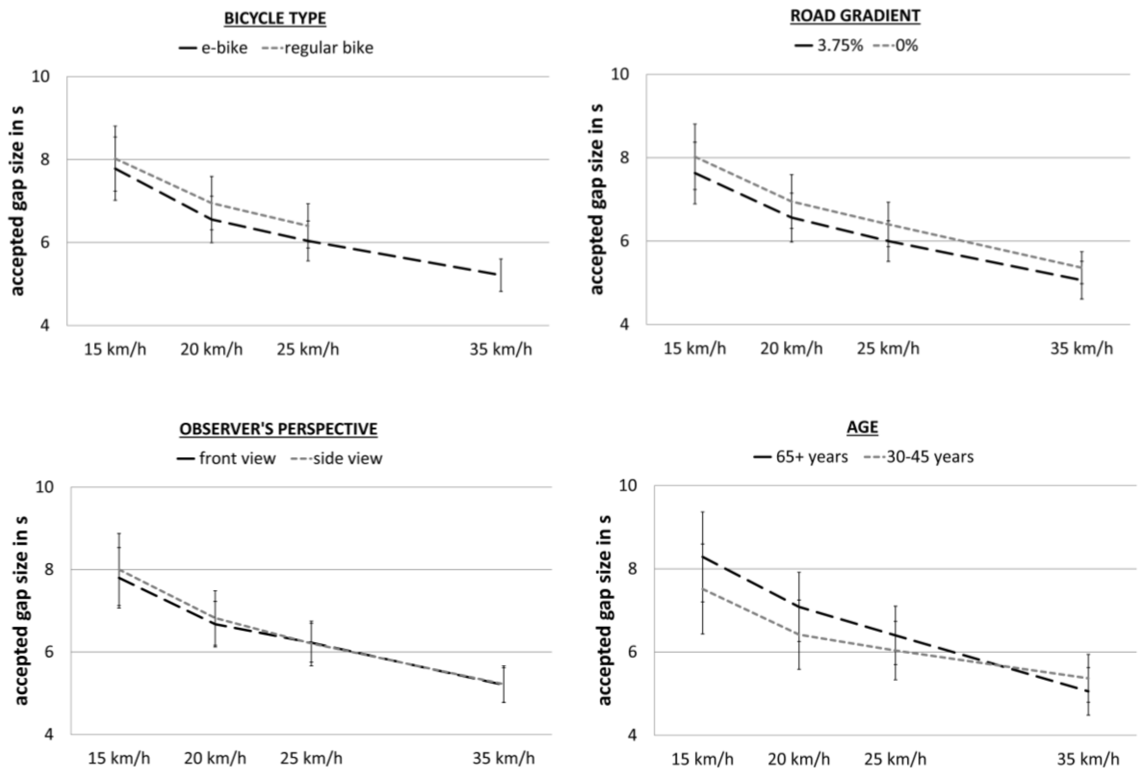

Figure 4. Accepted gap size for the different speed levels dependent on bicycle type (top left), road gradient (top right), observer's perspective (bottom left) and observer's age (bottom right). Error bars represent 95% confidence intervals.

As Table 3 shows, there was also an interaction between bicycle type and age group. The inspection of the data suggests that the main effect of bicycle type is mainly driven by the response of older participants, who chose an average gap of 7.0 s (*SD* = 2.1) in front of an approaching e-bike, and a gap of 7.6 s (*SD* = 2.4) in front of a conventional bicycle. There was no such difference for the younger group, which chose gaps of 6.6 s (*SD* = 1.6) and 6.7 s (*SD* = 1.5), respectively. In contrast, there was no interaction between speed and any of the other factors. The ANOVA also uncovered a three-way interaction between speed, gradient and age group. As Figure 5 shows, the effect of road gradient increased with increasing speed for the younger participants, whereas it slightly decreased for the older group.

Table 3. Summary of ANOVA results for the accepted gap size. Significant effects in boldface.

	F	p	η^2_p
speed	**68.95**	**<.001**	**.63**
bicycle type	**18.41**	**<.001**	**.32**
gradient	**12.21**	**.001**	**.23**
perspective	0.61	.438	.02
age group	1.02	.319	.03
speed x bicycle type	0.57	.570	.01
speed x gradient	0.49	.616	.01
speed x perspective	0.71	.495	.02
speed x age group	1.03	.316	.03
bicycle type x gradient	2.34	.142	.05
bicycle type x perspective	2.30	.138	.05
bicycle type x age group	**12.76**	**.001**	**.24**
gradient x perspective	0.26	.610	.01
gradient x age group	2.72	.107	.06
perspective x age group	2.99	.092	.07

speed x bicycle type x gradient	0.10	.907	<.01
speed x bicycle type x perspective	0.18	.835	<.01
speed x bicycle type x age group	0.34	.709	.01
speed x gradient x perspective	0.11	.894	<.01
speed x gradient x age group	**6.77**	**.002**	**.14**
speed x perspective x age group	2.97	.057	.07
bicycle type x gradient x perspective	<0.01	.957	<.01
bicycle type x gradient x age group	0.19	.663	<.01
bicycle type x perspective x age group	0.09	.762	<.01
gradient x perspective x age group	0.23	.635	.01
speed x bicycle type x gradient x perspective	0.03	.974	<.01
speed x bicycle type x gradient x age group	1.42	.247	.03
speed x bicycle type x perspective x age group	0.81	.451	.02
bicycle type x gradient x perspective x age group	1.00	.324	.02
speed x bicycle type x gradient x perspective x age group	1.80	.171	.04

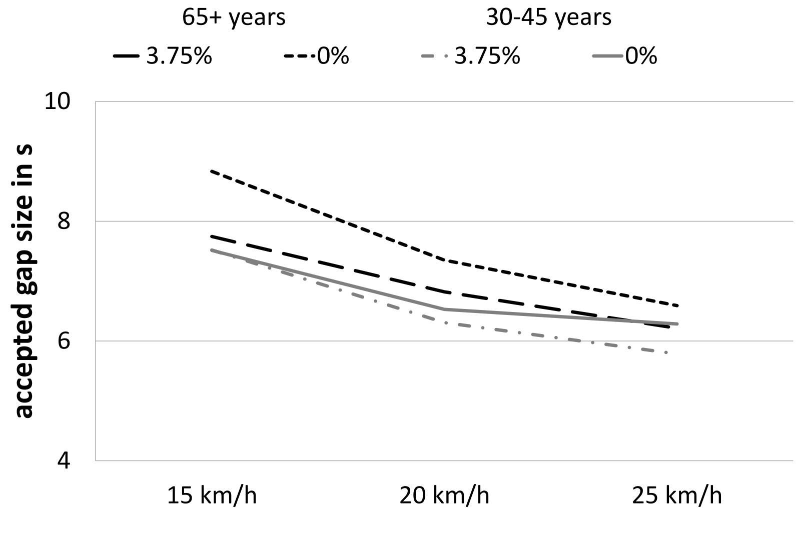

Figure 5. Three-way interaction between age group, road gradient and speed. (35 km/h condition and error bars omitted in this graph to increase legibility).

4 Discussion

Aim of the experiment was to investigate the influence of approach speed and bicycle type on drivers' gap acceptance. We found a clear effect of approach speed on the size of accepted gaps. The faster the oncoming bicycle was, the smaller were the gaps the participants selected for crossing/turning in front of the cyclist. Interestingly, the type of bicycle had an effect on accepted gap size as well. Selected gaps in front of oncoming e-bikes were significantly smaller compared to the gaps chosen when a conventional bicycle approached. This effect occurred although participants had no prior knowledge about the fact that different bikes were used (a few participants reported afterwards to have noticed the difference between the bicycles once they had passed their position, but also confirmed that they were unable to tell them apart in the approach situation).

One possible explanation for this effect is the potential difference in posture and pedalling frequency when using an e-bike compared to a conventional bicycle. As the pedalling support of an e-bike allows the rider to achieve higher speeds with less effort, pedalling frequency can be suspected to be, on average, lower than with a conventional bicycle. At the same time, the lower effort might also be reflected in the cyclists overall position and posture on the bicycle. This, as a whole, might convey the impression of a comparatively slow approach. The finding that the effect of bicycle type was especially strong in older participants confirms previous studies which reported that older drivers have problems in properly assessing the time it takes for an oncoming vehicle to arrive (Scialfa et al., 1991). If indeed the ability to judge an objects' approach is compromised, it appears reasonable to rely, consciously or not, on heuristics and prior knowledge, such as experience with a cyclist's usual look when he is riding at a certain speed. Unfortunately, the use of heuristics does not necessarily lead to good decisions, as has been demonstrated for example for (bicycle) overtaking situations (Walker, 2007).

Heuristics can also be suspected to have caused the effect of road gradient. To expect (again, consciously or not) that a bicycle approaching uphill is comparatively slow is, to some degree, reasonable. Other assumptions (e.g. it is easier to decelerate for the climbing cyclist) might add to this impression, resulting in smaller gaps accepted in front of oncoming cyclists that are riding uphill. However, we found no interaction between road gradient and speed. It appears that the effect is independent of whether the actual approach speed would be common (i.e. low) or uncommon (i.e. high) for the climbing scenario.

Worrisome is the finding that some participants accepted gaps that were smaller than the critical time gap. Although it has to be acknowledged that the chosen definition of the critical gap was rather simple, the specific shortcomings of the approach (neglect of response latencies, no consideration of safety margins) suggest that the 2.5% unsafe gaps might be an underestimation. Even when the indication to accept a gap and actual crossing/turning behaviour have been found to be not exactly congruent (te Velde et al., 2005), the fact that unsafe gaps are considered for crossing/turning is problematic. Coupled with the result that smaller gaps are chosen when the cyclists' approach speed is higher and when the oncoming bicycle is an e-bike, it can be suspected that electric bicycles are at increased risk of being involved in a safety critical situation.

Unfortunately, there is no obvious intervention that can help increase the size of accepted gaps in front of e-bikes in an instant. When following the assumption that heuristics play a role in gap acceptance, and that such heuristics might be responsible for the smaller accepted gaps in front of e-bikes, the conclusion must be to help road users develop new heuristics that also consider the e-bike and its behaviour. With increased exposure, one might assume that learning processes will lead road users to a different understanding of the speed of "bicycle-shaped vehicles", i.e. increased speed levels might become part of the mental model that is used for the crossing decision heuristic. However, it might be more effective to try establish e-bikes as a separate category of vehicle, distinct from conventional bicycles, e.g., by introducing visual features that help observers differentiate between the two vehicle types. Again, however, one should not expect such an intervention to yield effects immediately. Perceptual heuristics do usually not employ deliberate thought processes ("it looks different than a normal bike, I should be careful"), but are rather implicit rules (Hecht, 1996), learned through repeated practice. So, even when the e-bike is designed clearly distinct from conventional bicycles, road users will need time to experience and learn that the "thing not quite looking like a bicycle" does indeed not behave like a bicycle. But of course, this learning process can and should be supported by any means available.

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PAPER IV

THE INFLUENCE OF SPEED, CYCLISTS' AGE, PEDALLING FREQUENCY AND OBSERVER AGE ON OBSERVERS' TIME TO ARRIVAL JUDGEMENTS OF APPROACHING BICYCLES AND E-BIKES

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THE INFLUENCE OF SPEED, CYCLISTS' AGE, PEDALLING FREQUENCY AND OBSERVER AGE ON OBSERVERS' TIME TO ARRIVAL JUDGEMENTS OF APPROACHING BICYCLES AND E-BIKES

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Abstract

Given their potential to reach higher speed levels than conventional bicycles, the growing market share of e-bikes has been the reason for increased concerns regarding road safety. Previous studies have shown a clear relationship between object approach speed and an observers' judgment of when the object would reach a predefined position (i.e., time to arrival, TTA), with higher speed resulting in longer TTA estimates. Since TTA estimates have been linked to road users' decisions of whether or not to cross or turn in front of approaching vehicles, the higher potential speeds of e-bikes might result in an increased risk for traffic conflicts. The goal of the two experiments presented in this paper was to examine the influence of speed and a variety of other factors on TTA estimation for conventional bicycles and for e-bikes. In both experiments, participants from two age groups (20-45 years old and 65 years or older) watched video sequences of bicycles approaching at different speeds (15 - 25 km/h) and were asked to judge the TTA at the moment the video was stopped. The results of both experiments showed that an increase in bicycle approach speed resulted in longer TTA estimates (measured as the proportion of estimated TTA relative to actual TTA) for both bicycle types ($\eta_p^2{}_{Exp.1} = .489$, $\eta_p^2{}_{Exp.2} = .705$). Compared to younger observers, older observers provided shorter estimates throughout (Exp. I: $M_{Diff} = 0.35$, CI [.197, .509], $\eta_p^2 = .332$, Exp. II: $M_{Diff} = 0.50$, CI [.317, .682], $\eta_p^2 = .420$). In Experiment I, TTA estimates for the conventional bicycle were significantly shorter than for the e-bike ($M_{Diff} = 0.03$, CI [.007, .044], $\eta_p^2 = .154$), as were the estimates for the elder cyclist compared to the younger one ($M_{Diff} = 0.05$, CI [.025, .066], $\eta_p^2 = .323$). We hypothesized that the cause for this effect might lie in the seemingly reduced pedaling effort for the e-bike as a result of the motor assistance it provides. Experiment II was able to show that a high pedaling

frequency indeed resulted in shorter TTA estimates compared to a low one (M_{Diff} = 0.07, *CI* [.044, .092], η_p^2 = .438). Our findings suggest that both the e-bikes' potential to reach higher speeds and the fact that they reduce the perceived cycling effort increase the risk of TTA misjudgments by other road users.

Keywords: electric bicycles, time to collision, ageing, intersection

1 Introduction

In recent years, electric bicycles (e-bikes) have become increasingly popular (Rose, 2012). In Germany, already 1.6 million e-bikes are on the road (Zweirad-Industrie-Verband, 2014) and sales figures are expected to grow even more (Jellinek, Hildebrandt, Pfaffenbichler, & Lemmerer, 2013). Reasons for that popularity are that e-bikes offer a reduction in cycling effort, the possibility to compensate for physical impairments, and the potential to reach farther destinations more easily (Jellinek et al., 2013; Kuratorium für Verkehrssicherheit, 2011; Schleinitz et al., 2014). While these are desirable outcomes, not all potential consequences of the increased popularity are positive. In particular, safety concerns have been raised because the design of e-bikes is hardly distinguishable from that of conventional bicycles. However, in comparison, e-bikes reach higher mean and maximum speeds (Schleinitz et al., in press) and it has been argued that this could result in other road users misjudging the speed of an approaching e-bike (bfu-Beratungsstelle für Unfallverhütung, 2014; Skorna et al., 2010). An e-bike user described it this way: "I had to be really conscientious of other drivers because they weren't expecting me to approach as quickly as I was. And so, in the beginning, I feel like cars were kind of cutting me off because they thought they had plenty of time." (Popovich et al., 2014, p. 42).

Unfortunately, actual crash statistics to support the assumption that e-bike riders are at an increased risk to be involved in a crash are not readily available. Data from China (Feng et al., 2010) appear to provide some evidence, with rates of casualties and injuries due to crashes involving an e-bike having increased over a period of five years, even after adjusting for growth of the e-bike population. However, an application of these findings to Western countries is limited since most of the two-wheelers that are categorized as e-bikes in China would be characterized as mopeds in Europe or the in the US. First data from Switzerland show a rise in the absolute number of crashes that involved e-bikes which resulted in severe injuries and causalities, however those numbers do not control for the fact that sales figures of e-bikes also increased (bfu-Beratungsstelle für Unfallverhütung, 2014). Findings from a naturalistic cycling study, which observed riders of conventional bicycles and riders of e-bikes for a period of four weeks found that, while overall risk was comparable, e-bike riders were at higher risk of being involved in a safety critical event in the direct vicinity of an intersection. It also appeared that motorists failed more often to yield to an e-bike than to a conventional bicycle (Petzoldt, Schleinitz, Heilmann, & Gehlert, 2015; Schleinitz et al., 2014). Data show that in collisions with e-bikes, the second party involved was found to be at fault in 70% of all cases, compared to 61% for conventional bicycles. According to the authors, this suggests that others underestimate the speed of the e-bike rider (Scaramuzza, Uhr, & Niemann, 2015). This might be somewhat surprising, as drivers have to estimate speed, or, more precisely, time to collision (TTC) or time to arrival (TTA), "the time remaining before something reaches a person or particular place" (Tresilian, 1995, p. 231), on a regular basis. However, it is well established that, while in general the human ability to estimate TTA is sufficiently accurate, it is also prone to a variety of biases and errors.

Several experiments have shown an effect of speed on TTA estimation (e.g. Manser, 1999; Petzoldt, 2014; Recarte, Conchillo, & Nunes, 2005). Results from all of these studies indicate that higher speeds go with longer TTA estimates (which in turn should result in riskier driver decisions). Unfortunately, the speed levels that were studied ranged from 30 km/h to 120 km/h, i.e., they are hardly relevant for bicycles. However, the clear trends observed in these studies allow for the assumption that also at cycling speed levels, higher speeds (as they would be reached by e-bikes) would be accompanied by longer TTA estimates.

Another aspect that is linked to the specific features of e-bikes is the fact that they are, at least at the moment, attractive to a very specific user group. In Germany, for example, e-bike users are, on average, ten years older than conventional cyclists (Preißner, Kemming, Wittkowsky, Bülow, & Stark, 2013). From other contexts, it is known that strong stereotypes exist in regards to the behavior of older road users. In a study by Joanisse, Gagnon and Voloaca (2012), participants watched video clips with car drivers performing different driving behaviors and afterwards were asked to indicate how representative they thought the observed behavior was for a typical older driver. Not surprisingly, it was found that driving slowly was considered representative for older driver behavior. Similar findings were reported by Davies and Patel (2005). Since cycling and especially cycling speed are dependent on physical fitness, it is reasonable to assume that such stereotypes play also a role in the perception of bicyclists. How far this translates into differences in perceived approach speed is a question that, as of now, has not been answered.

However, not only the observer's perceptions of the rider and the riders' speed might have an impact on TTA judgments of approaching bicyclists. The age of the observer has been repeatedly found to have an influence on judgments of time gaps as well. In a study by Schiff, Oldak and Shah (1992), older participants showed a significantly poorer accuracy in TTA estimations than younger participants. Their estimates were consistently shorter than those made by younger observers, i.e., older participants perceived vehicles as arriving much earlier. Comparable results were also be found by Hancock and Manser (1997). Again, however, it is unclear if the same effects occur with considerably lower cycling speeds.

Therefore, the main interest of our experiments was to evaluate whether and to what extent variations in speed would result in corresponding variations in TTA estimates. For that purpose, two experiments were conducted to investigate the effects of speed and bicycle type (i.e., bicycle versus e-bike) on an individual’s TTA estimation. In addition, in Experiment I we examined the influence of the cyclist’s age. In Experiment II, we varied pedaling frequency, a manipulation that was suggested by the results of the first experiment. Finally, in both experiments we investigated whether the age of the observer had an influence on TTA estimations.

2 Experiment I

The purpose of Experiment I was to investigate the influence of approach speed, cyclist’s age, and bicycle type on the TTA estimations of older and younger observers. Based on prior studies, we hypothesized that older observers would provide shorter TTA estimates than younger observers would. To extend the results of studies investigating TTA estimates of approaching cars, we predicted that an increase in speed would also lead to longer TTA estimations for smaller vehicles like bicycles. Based on results about the effects of stereotypes regarding the age of car drivers, that slower driving is representative of older people (Joanisse et al., 2012), we expected that an older cyclist would be estimated to arrive later than a younger one. In addition, we varied the bicycle type, using both a conventional bicycle and an e-bike.

2.1 Method

2.1.1 Participants

We acquired a sample of 44 participants for two predefined age groups (22 persons per group). The younger participants (20-45 years old) were on average 33.3 years old (SD = 8.1), the older ones (65 years and older) were on average 71.3 years old (SD = 3.7). Twenty-one participants were male and twenty-three were female (20-45 years: 8 male, 14 female, ≥ 65 years: 13 male, 9 female). All participants were in possession of a valid driving license. All had normal or corrected to normal visual acuity. For their participation, they received monetary compensation.

2.1.2 Experimental design

To address our hypotheses, we designed a video-based laboratory experiment in which different bicycles approached a stationary observer. The experiment made use of a mixed design where the age group of the observer was treated as a between subjects factor (see Table 1). The approaching vehicles were a conventional trekking bicycle (Diamant Ubari black) and a comparable e-bike (Diamant Supreme, Figure 1). Both types of bikes were ridden by either a typical older (65 years) or younger cyclist (28 years). They were riding at constant speeds of either 15, 20, or 25 km/h. Furthermore, we used three different TTAs in order to avoid that the participants adapt to a single TTA value. This resulted in a total of 36 combinations that were presented in random order to the participants. The estimated TTA was treated as the dependent variable.

Figure 1. Conventional bicycle (left) and e-bike (right) used in the experiment.

Table 1. Overview over all factors and factor levels.

Observer age	Bicycle type	Cyclist's age	Speed	TTA
20-45 years	conventional bicycle	young	15 km/h	4 s
≥ 65 years	electric bicycle	old	20 km/h	6 s
			25 km/h	8 s

2.1.3 Material

We used real world video scenes of approaching bicycles (Figure 2) which were recorded on a straight taxiway of a small general aviation airport. All scenes were recorded from a driver's point of view, i.e. the height of the camera position is comparable to the eye level of a driver sitting in a car. Figure 3 shows the bird's eye view of the scenario. We pasted a white line on the street surface that marked the position of a potential collision between the oncoming cyclist and the observer when turning left. All combinations of bicycle type, cyclist's age, and speed were filmed. When riding the e-bike our cyclists received no instructions as to how much assistance from the motor they should use. Instead, they were asked to use the level of assistance they considered suitable for the intended speed level and to have a setting that was as natural as possible. In general, our cyclists were free to choose an appropriate gear to reach each speed level. The recorded material was then cut into clips of 4 s length, with the end of each video clip set according to the three TTA levels. The material was then presented to our participants using a projector (projection image 125 x 220 cm) in order to give the participants a more realistic view of the cyclists. Participants were seated at a desk at a distance of 250 cm from the screen. The visual angle of the oncoming bicycle, including the rider, ranged from 1.87° to 4.67° (based on the last frame of the video before the bicycle was occluded) independent of bicycle and cyclist's age (Table 2).

Table 2. Overview over all factors and factor levels.

Speed	TTA	Visual angle
15 km/h	4 s	4.67°
	6 s	3.42°
	8 s	2.80°
20 km/h	4 s	3.74°
	6 s	2.80°
	8 s	2.28°
25 km/h	4 s	3.22°
	6 s	2.39°
	8 s	1.87°

2.1.4 Procedure

First, participants received instructions on the experiment. We explained that their task was to watch one short video clip at a time and while observing the approaching cyclist, participants were asked to put themselves in the position of a car driver at an intersection, waiting to make a left turn. After the clip ended (4 s runtime), the screen was blank and participants were asked to indicate the moment when they thought the bicycle would reach the white line by pressing the spacebar. After having been explained the procedure, the participants completed two practice trials to become familiar with the task. Then, in the experimental phase, they were presented with one clip for each factor combination, which resulted in 36 trials. The complete session lasted 15 to 20 minutes.

Figure 2. Screenshot from one of the video sequences (i.e., the observer's perspective). The horizontal white line marked the position of a potential collision between the oncoming cyclist and the observer (when turning left). The dotted line represents the observer's hypothetical left-turn trajectory.

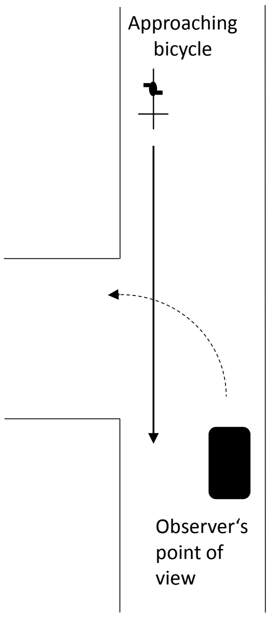

Figure 3. Bird's eye view of the intersection. The solid line represents the trajectory of the approaching cyclist. The dotted line represents the observer's hypothetical left-turn trajectory.

2.1.5 Analysis

For a description of the overall accuracy of the participants' responses (i.e., absolute error), figures 4 to 6 display mean estimated TTA for the three TTA levels. For inferential statistics, we collapse the data across TTA levels since these levels were only introduced to provide some variation in the material and to avoid undesired learning effects. To collapse the data across TTA levels, a transformation of the raw estimates was necessary. For the transformation, we calculated a TTA estimate ratio, which was the proportion of estimated TTA relative to the actual TTA (e.g. Schiff & Oldak, 1990):

$$\text{TTA estimate ratio} = \text{estimated TTA} / \text{actual TTA}$$

A value above 1 indicates an overestimation of the TTA and a value lower than 1 indicates an underestimation. We found no significant differences between the TTA estimate ratios of the different levels ($F\ (2, 84) = 2.19$, $p = .118$, $\eta 2p = 0.050$) so we then created a single composite score for the main analysis, which was the mean of the three ratios. With the remaining factors, we conducted a four-factor analysis of variance (ANOVA) for mixed designs. Bonferroni correction was used for all pairwise comparisons.

2.2 Results

In Figures 4, 5, and 6, participants' actual TTA estimates are illustrated. As can be seen from the graphs, TTA estimates increased with increasing speed, although the objective TTA was the same. This impression was confirmed by the ANOVA based on the TTA ratios (see Table 3 for an overview of all main effects and interactions). Pairwise comparisons showed significant differences between all three speed levels (all $p < .001$).

Contrary to our previous assumption, actual TTA estimates for the older cyclist were shorter than for the younger cyclist at each of the three TTA levels (Figure 4). The ANOVA indicated significantly lower TTA ratios for the older cyclist ($M = 0.60$; $SD = 0.29$) than for the younger cyclist ($M = 0.65$; $SD = 0.31$).

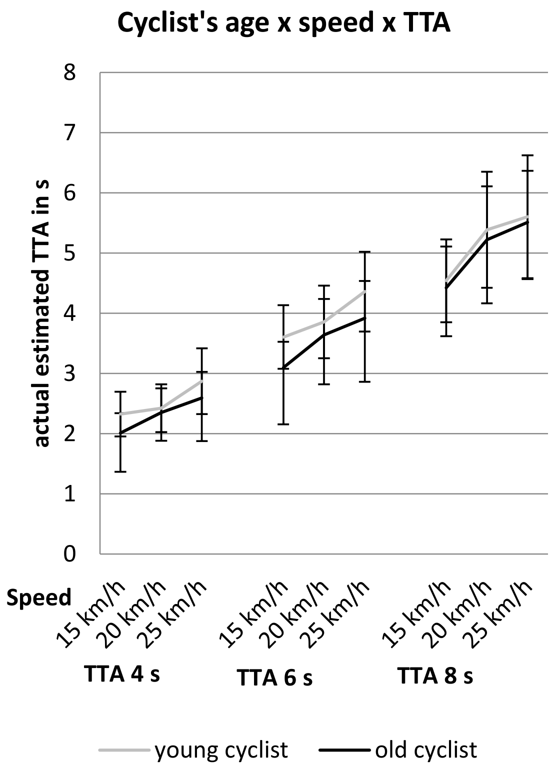

Figure 4. TTA estimates for the different speed levels dependent on cyclist's age. Error bars represent 95% confidence intervals.

Also somewhat surprisingly was we found a significant difference between the two bicycle types (Figure 5), with TTA estimate ratios for the conventional bicycle significantly lower (*M* = 0.61; *SD* = 0.30) than for the e-bike (*M* = 0.64; *SD* = 0.32). There was also a significant interaction between bicycle type and the cyclist's age. The lowest TTA ratios were measured for the older rider on a conventional bicycle (*M* = 0.57; *SD* = 0.29) whereas there were practically no differences between the other three rider-bicycle combinations ($M_{ebike\text{-old}}$ = 0.63, *SD* = 0.31; $M_{ebike\text{-young}}$ = 0.64, *SD* = 0.34; $M_{bicycle\text{-young}}$ = 0.65, *SD* = 0.33).

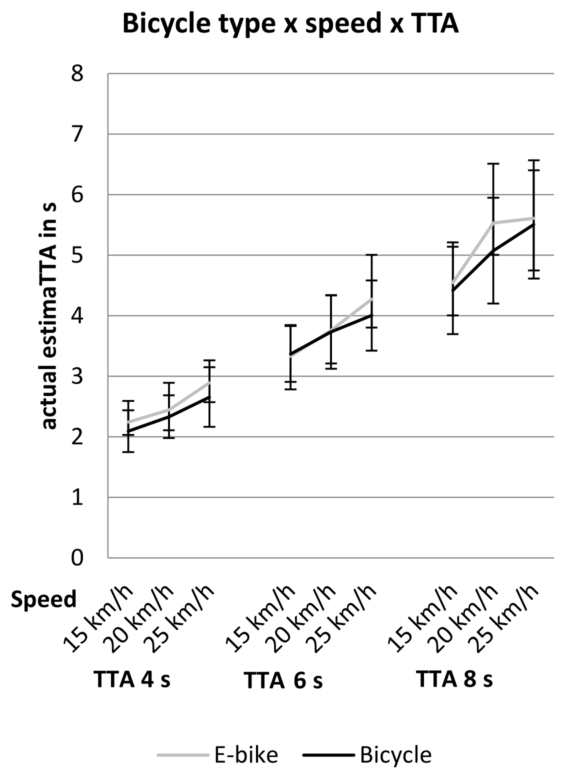

Figure 5. TTA estimates for the different speed levels dependent on bicycle type. Error bars represent 95% confidence intervals.

The observers' age had a significant influence on TTA estimates as well. Older participants provided substantially shorter TTA estimates than the younger participants (Figure 6). The ANOVA revealed significantly lower TTA ratios for the older group (M = 0.45, SD = 0.17) compared to the younger group (M = 0.80, SD = 0.32). In addition, we found a significant interaction between observer age and age of the cyclist. The data show that while older participants did not really differentiate between the two riders (M_{old} = 0.44, SD = 0.16; M_{young} = 0.46, SD = 0.17), the younger participants judged the older cyclist (M = 0.77, SD = 0.30) as arriving considerably earlier than the younger cyclist arrived (M = 0.83, SD = 0.33). Likewise, a significant interaction between speed and observer age was found. For the younger group, the TTA estimate ratios rose more steeply with increasing speed ($M_{young\ 15}$ = 0.71, SD = 0.26; $M_{young\ 20}$ = 0.81, SD = 0.36; $M_{young\ 25}$ = 0.88, SD = 0.37) in comparison to the TTA estimate ratios of the older group ($M_{old\ 15}$ = 0.40, SD = 0.16; $M_{old\ 20}$ = 0.45, SD = 0.16; M_{old25} = 0.50, SD = 0.18). In addition, we found a significant interaction between speed, cyclist's age, and bicycle type, for which no meaningful interpretation was possible.

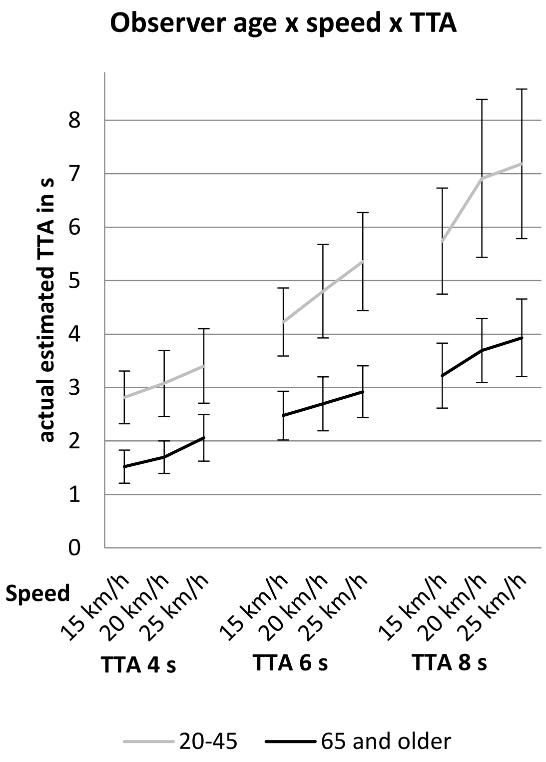

Figure 6. TTA estimates for the different speed levels dependent on observer age. Error bars represent 95% confidence intervals.

Table 3. Summary of ANOVA results for TTA estimate ratio (significant effects in boldface).

	df	*F*	*p*	η_p^2
bicycle type	**1, 42**	**7.67**	**.008**	**.154**
cyclist‘s age	**1, 42**	**20.01**	**<.001**	**.323**
speed (*GGc)	**1.515, 63.637**	**41.60**	**<.001**	**.498**
observer age	**1, 42**	**20.91**	**<.001**	**.332**
bicycle type * observer age	1, 42	.10	.753	.002
cyclist’s age * observer age	**1, 42**	**5.00**	**.031**	**.106**
speed * observer age	**2, 84**	**3.30**	**.042**	**.073**
bicycle type * cyclist‘s age	**1, 42**	**11.19**	**.002**	**.210**
bicycle type * speed (*GGc)	1.638, 68.791	.32	.687	.007
cyclist’s age * speed (*GGc)	1.647, 69.192	.86	.410	.020
bicycle type * cyclist‘s age * observer age	1, 42	.13	.724	.003
bicycle type * speed * observer age	2, 84	2.54	.085	.057
cyclist‘s age * speed * observer age	2, 84	.72	.491	.017
bicycle type * cyclist‘s age * speed (*GGc)	**1.645, 69.075**	**6.46**	**.005**	**.133**
bicycle type * cyclist‘s age * speed * observer age	2, 84	.49	.614	.012

Note: *GGc = Greenhouse-Geisser correction

3 Experiment II

The finding in Experiment I, that the e-bike was judged as arriving later than the conventional bicycle, was somewhat surprising since the two bicycles were chosen to be as similar as possible in terms of their design. From the video, it was impossible to differentiate between them (this was confirmed by the participants). Consequently, a possible explanation for this effect does not lie in the observers’ perception of the bicycle, but its rider instead. It appears that human perception is especially attuned for the biological motions of others (Johansson, 1973; Vanrie & Verfaillie, 2004). This perception of motion is often used to infer states, traits, intentions, and future actions of the observed. Schmidt and Färber (2009), for example, provided evidence that drivers use pedestrians' posture and movement to infer a crossing intention. They noted that "there appears to be something special to the human motion which is necessary for intention recognition" (p. 307). Hemeren et al. (2014) found similar results for the prediction of cyclists' behavior.

With the e-bike providing pedaling support to the rider, the riders' effort, and especially his pedaling frequency, decreases when compared to riding a conventional bicycle at the same speed. An observer might interpret this comparatively low effort as an indicator for lower speed. This might also explain the finding that the older rider was perceived as arriving earlier than the younger one. During a second inspection of the video material the impression arose that, not surprisingly, it seemed like the older rider expended much more effort than the younger rider did to achieve the same speed. The observers might have interpreted this increased effort as an indicator for a somewhat higher speed. Because of the findings of Experiment I, the aim of Experiment II was to assess the effect of pedaling frequency on estimated TTA.

Assuming that the perceived rider effort, and not the bicycle type (or the rider's age), was responsible for the findings of the first experiment, the effect of bicycle type should disappear when we control for pedaling frequency. Aside from pedaling frequency and bicycle type, we also varied approach speed and observer age, again expecting longer estimates with increased speed and shorter estimates from older observers.

3.1 Method

3.1.1 Participants

Participants consisted of 22 younger (20-45 years, *M* = 33.0, *SD* = 7.8) and 22 older adults (≥ 65 years, *M* = 71.3 years, *SD* = 3.7). Twenty- two participants were male and twenty-two were female (20-45 years: 9 male, 13 female, ≥ 65 years: 13 male, 9 female). All participants had normal or corrected-to-normal visual acuity and all of them had a valid driving license. Like in Experiment I, participants received monetary compensation for their participation.

3.1.2 Experimental design

Table 4 displays the factors and factor levels of this experiment. The mixed design again included observer age as a between-subjects factor. The three speed levels, two vehicle types, and three TTAs (which were again included only to avoid learning effects) were identical to Experiment I. As a new factor, we introduced a variation of pedaling frequency (two levels). This resulted in a total of 36 within factor level combinations that were then presented randomly to the participants. As dependent variable, we again measured the participants' estimation of TTA.

Table 4. Overview over all factors and factor levels.

Observer age	Bicycle type	Pedalling frequency	Speed	TTA
20-45 years	conventional bicycle	Low (90 beats/minute)	15 km/h	4 s
≥ 65 years	electric bicycle	High (155 beats/minute)	20 km/h	6 s
			25 km/h	8 s

3.1.3 Material

The video material used in this experiment was comparable to the sequences in Experiment I. Again, we recorded a cyclist approaching on both bicycle types, at all of the three speed levels. The two different levels of pedalling frequency were created with the help of a metronome, which was played to the rider through an MP3 player. The metronome produced either 90 beats per minute (low condition) or 155 beats per minute (high condition), with the cyclist required to complete half a revolution per beat. Videos were again cut into 4s clips, with the approaching bike at a time distance of one of the three TTA levels at the end of the clips. The material was presented with a projector (projection image 125 x 220 cm), with a distance of 250 cm between participant and screen. The visual angle of the oncoming bicycle, including the rider, ranged from 1.76° to 4.67° (final video frame before occlusion, Table 5).

Table 5. Overview over all factors and factor levels.

Speed	TTA	Visual angle
15 km/h	4 s	4.67°
	6 s	3.42°
	8 s	2.70°
20 km/h	4 s	3.74°
	6 s	2.80°
	8 s	2.18°
25 km/h	4 s	3.22°
	6 s	2.39°
	8 s	1.76°

3.1.4 Procedure

The experimental procedure and room were the same as in Experiment I. Participants were presented with instructions and two practice trials before the 36 experimental trials were completed. Their task was again to indicate the arrival of the bicycle at the white line by pressing the space bar. The complete session lasted 15 to 20 minutes.

3.1.5 Analysis

The analysis procedure was identical to the one in Experiment I. As we found no significant differences regarding the TTA estimates between the different TTA levels, F (2, 84) = 3.24, p = .051, η^2_p = 0.072, we collapsed across TTA levels for the main analysis. A 4 factor mixed-design ANOVA was conducted for the TTA estimates ratio. Bonferroni correction was used for the pairwise comparison.

3.2 Results

Figures 7, 8 and 9 display the actual estimated TTAs for speed depending on the factors bicycle type, pedalling frequency and observer age for each of the TTA levels. As in Experiment I, the effect of speed on TTA estimates was highly significant (see Table 6 for an overview of all main effects and interactions), with higher speeds being associated with increased TTA estimates. Pairwise comparisons revealed significant differences between all three speed levels (all p < .001).

Bicycle type (Figure 7), on the other hand, had no longer a significant influence on TTA ratios, with nearly identical mean values for the conventional bicycle (M = 0.75, SD = 0.40) and the e-bike (M = 0.76, SD = 0.38). However, there was an interaction between bicycle type and speed. For 15 and 20 km/h, TTA estimates as well as the ratios were lower for the conventional bicycle than for the e-bike ($M_{\text{bicycle 15}}$ = 0.66, SD = 0.37; $M_{\text{bicycle 20}}$ = 0.73, SD = 0.39; $M_{\text{e-bike 15}}$ = 0.68, SD = 0.37; $M_{\text{e-bike 20}}$ = 0.78, SD = 0.40), whereas for 25 km/h, TTA estimates ratios were lower for the e-bike ($M_{\text{bicycle 25}}$ = 0.86, SD = 0.47; $M_{\text{e-bike25}}$ = 0.83, SD = 0.39).

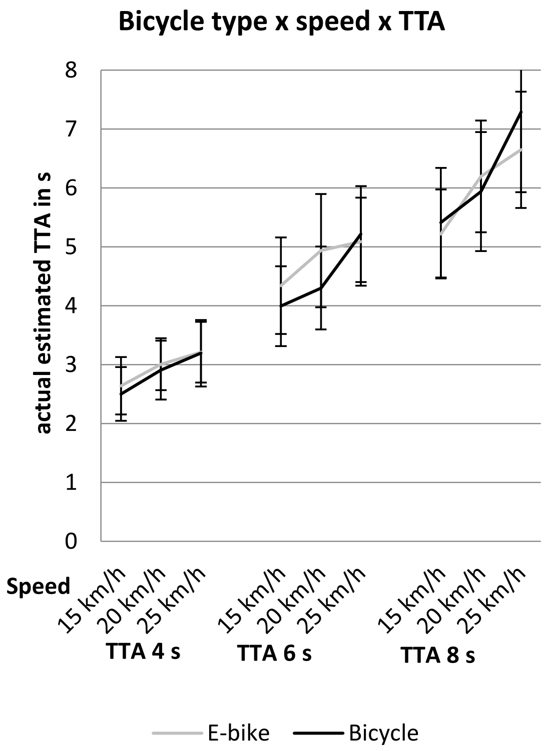

Figure 7. TTA estimates for the different speed levels dependent on bicycle type. Error bars represent 95% confidence intervals.

While bicycle type no longer played a role in TTA estimates, we found a significant main effect of pedalling frequency. The actual estimated TTA for the higher pedalling frequency was clearly shorter than the estimates for the lower frequency (Figure 8). As a consequence, the TTA ratio for the lower pedalling frequency was significantly smaller (M = 0.72, SD = 0.38) than for the higher pedalling frequency (M = 0.79, SD = 0.41), i.e., participants perceived a bicyclist with a higher pedalling frequency as arriving earlier compared to a cyclist with a lower frequency. As expected, the age of our participants had a significant effect as well (Figure 9), as for our older group the TTA ratios were much lower (M = 0.51, SD = 0.15) than the younger participants (M = 1.01, SD = 0.40).

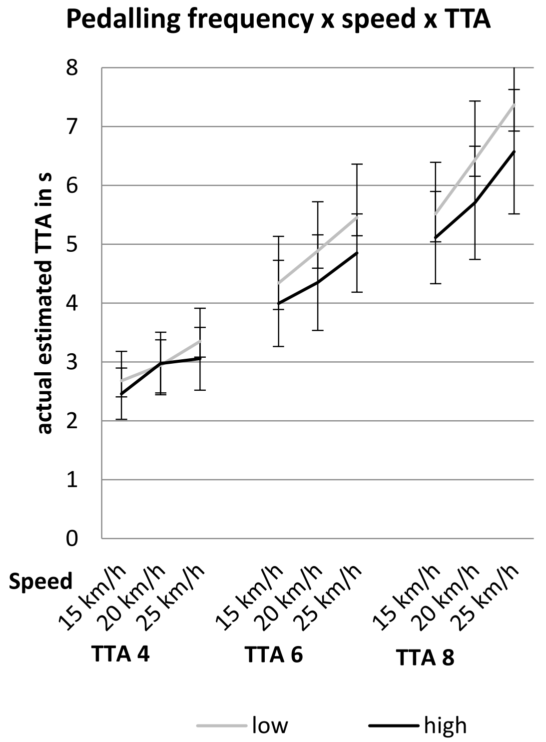

Figure 8. TTA estimates for the different speed levels dependent on pedalling frequency. Error bars represent 95% confidence intervals.

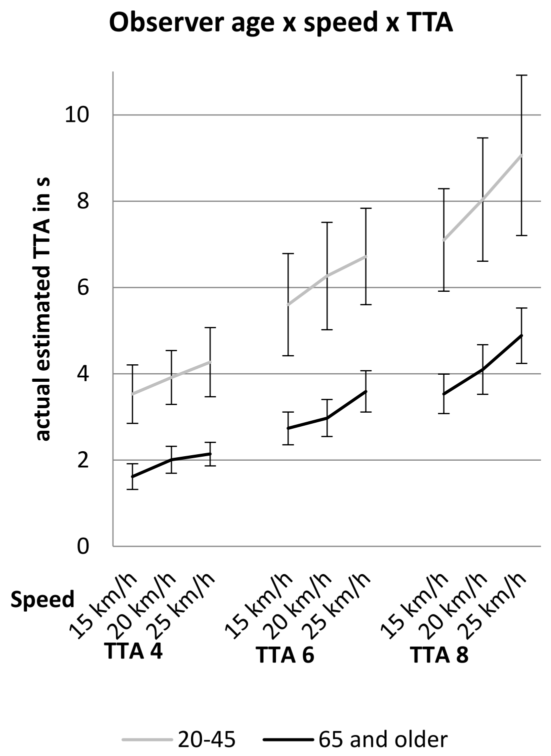

Figure 9. TTA estimates for the different speed levels dependent on observer age. Error bars represent 95% confidence intervals.

Table 4. Summary of ANOVA results for TTA estimate ratio. Significant effects in boldface.

	df	*F*	*p*	η_p^2
bicycle type	1, 42	2.88	.097	.064
pedalling frequency	**1, 42**	**32.67**	**< .001**	**.438**
speed (*GGc)	**1.604, 67.383**	**100.22**	**< .001**	**.705**
observer age	**1, 42**	**30.47**	**< .001**	**.420**
bicycle type * observer age	1, 42	.03	.876	.001
pedalling frequency * observer age	1, 42	2.18	.148	.049
speed * observer age	2, 84	2.85	.064	.063
bicycle type * cadence	1, 42	.01	.949	.000
bicycle type * speed (*GGc)	**1.755, 73.722**	**3.99**	**.027**	**.087**
pedalling frequency * speed (*GGc)	1.719, 72.197	1.14	.320	.026
bicycle type * pedalling frequency * observer age	1, 42	.01	.908	.000
bicycle type * speed * observer age	2, 84	1.72	.185	.039
bicycle type * pedalling frequency * speed	2, 84	.19	.825	.005
pedalling frequency * speed * observer age	2, 84	1.20	.307	.028
bicycle type * pedalling frequency * speed * observer age	2, 84	.01	.997	.000

Note: *GGc = Greenhouse-Geisser correction

4 Discussion and conclusions

We conducted two experiments examining the TTA estimations of approaching bicycles, in which approach speed, bicycle type, cyclist's age, pedaling frequency, and observers' age were tested as influencing factors on TTA judgments. Experiment I showed a large effect of the cyclist's approach speed, observer's age, cyclist's age, and bicycle type on TTA estimation. The results for bicycle type suggested that the perception of the rider's motion had an effect on the TTA estimates since the e-bike, although visually indistinguishable from the conventional bicycle, was judged as arriving significantly later. It was hypothesized that the reduced cycling effort when riding an e-bike, e.g. through a reduced pedaling frequency, might be the source of this difference in perception. This hypothesis was tested in Experiment II. Indeed, the results showed a large effect of pedaling frequency on TTA estimations; cyclists approaching with a higher pedaling frequency were judged to be arriving earlier than cyclists pedaling with a lower frequency are. Moreover, the effect of pedaling frequency was independent of bicycle type, i.e., for both, the e-bike and the conventional bicycle, higher pedaling frequencies were associated with shorter TTA estimates. At the same time, there was no longer an effect of bicycle type on participants TTA estimates. This result underlines the relevance of the cyclist's motion pattern for TTA estimation.

In both experiments, we found that the age of the observer had a strong effect on TTA estimates, with older participants consistently providing shorter estimates than younger observers did. This finding confirms results from previous studies (e.g. DeLucia, Bleckley, Meyer, & Bush, 2003; Hancock & Manser, 1997; Schiff et al., 1992). Unfortunately, although this finding should mean that older participants make safer decisions on the road (Scialfa, Lyman, Kline, & Kosnik, 1987), DeLucia et al. (2003) found no correlations between TTA judgments and driver performance measures. Based on further results, they argued that older drivers have problems judging whether or not a collision would even occur, because they have problems accounting for the trajectory of the approaching object. This, in their interpretation, could be one potential explanation for the increased crash rates of older drivers.

The results from both experiments make it clear that approach speed has a considerable impact on TTA estimates, with increases in speed resulting in longer TTA estimates. While similar findings have been reported in regards to TTA estimates for motorized vehicles (e.g. Horswill, Helman, Ardiles, & Wann, 2005; Manser, 1999), our results are the first to confirm these findings for the cycling domain with its comparatively slower speeds. In addition, the fact that our relatively minor speed variations (in steps of 5km/h) still provoked this effect is an indicator for the stability of the phenomenon. This might be seen as slightly alarming, since the close link between TTA estimate and crossing decision (Petzoldt, 2014) implies that riders of e-bikes, with their potential to travel at higher speed, should be considered as being at an increased risk for collisions.

This issue is further complicated by the fact that approaching e-bikes were judged as arriving later than conventional bicycles. As Experiment II showed, this effect is mainly driven by a perceived reduction in effort by the cyclist, due to a reduced pedaling frequency. The interpretation that perceived pedaling effort is an indicator of the cyclist's speed also helps explain the apparently counterintuitive finding that the older cyclist was perceived to have arrived earlier than the younger one. The situation in which an e-bike rider approaches another party with seemingly low effort, but at relatively high speeds, must therefore be considered a situation prone to misperception by the other party.

Additional problems arise when comparing bicycles (in general) to other vehicles. It has repeatedly been reported that larger vehicles (e.g. Caird & Hancock, 1994), and larger objects in general (e.g. DeLucia, 1999; van der Kamp et al., 1997), are judged to arrive earlier than smaller ones. This so called size-arrival-effect has even been suspected to be the cause of a considerable number of car drivers' right-of-way violations in interactions with motorcycles (Horswill et al., 2005). As cyclists and their bicycles are probably physically the smallest group of road users, it has to be assumed that the high number of turning crashes between motorized vehicles (mainly those with four wheels) and cyclists are also a result of TTA overestimations. Overall, these findings indicate that there is no simple solution to the problem of a potential misperception regarding the TTA estimate of an e-bike rider.

A first step towards such a solution might be to increase road user awareness of the fact that there is a growing presence of vehicles on the road that might look like conventional bicycles, but are possibly travelling much faster. Road safety organizations should take on the responsibility of educating other road users about electric bicycles and their capabilities (Bohle, 2015). Unfortunately, currently e-bike users themselves also have to be prepared that other road users might be unaware of the presence of e-bikes on the road, and thus should expect unsafe turning or crossing maneuvers in front of them.

A step beyond the mere provision of more information would be to increase the distinctiveness of e-bikes through design changes, to allow for a better differentiation between them and conventional bicycles. It is clear that road users are hardly able to visually distinguish between conventional bicycles and e-bikes, which is a problem. The view of a certain vehicle leads road users to form expectations about this vehicle's behavior, including its acceleration and speed (Cherry & Andrade, 2001; Davies, 2009). Such expectations help to ease the decision making process. E.g., knowing that bicycles are usually rather slow helps to make a crossing decision in which a bike is in a considerable distance, without the need to actually observe the bicycle's approach. After all, given its limitations, there should be no chance that the bicycle is so fast that a collision would be even possible. However, the behavior of e-bikes does not necessarily match such expectations. Therefore, it appears necessary to make it clear to other road users that the bicycle-shaped vehicle that is coming towards them is, in fact, not a conventional bicycle. While such an approach would not eliminate the size-arrival-effect, it would reduce judgmental errors that occur because road users erroneously assume that the vehicle coming towards them is an ordinary bicycle when in fact it is an e-bike.

In addition, it might be assumed that, once the market penetration of e-bikes is high enough so that other road users have been able to experience them on a regular basis, their speed should no longer come as a surprise. However, given the persistence of the effects of speed or size of vehicles in general on TTA estimates, it is unrealistic to expect a clearer differentiation or an increase of exposure to fully eradicate any apparent misperceptions of an e-bikes approaching speed. The fact that differences in TTA estimation can still be found for long established vehicle types suggests that the unfavorable effects we found for e-bikes will not completely disappear, regardless of the measures that might be taken.

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CURRICULUM VITAE

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Professional experience

Since 07/2015	Project staff IAOV GmbH Institut für Arbeits-, Organisations- und Verkehrsforschung Chemnitz	Chemnitz
Since 09/2010	Researcher and lecturer at the Professorship of Cognitive and Engineering Psychology, Chemnitz University of Technology, Chemnitz	Chemnitz
10/2009 – 09/2010	Diplom-Psychologin Fortbildungsakademie der Wirtschaft Akademie Chemnitz	Chemnitz
04/2009 – 10/2009	Project staff IAOV GmbH Institut für Arbeits-, Organisations- und Verkehrsforschung Chemnitz	Chemnitz
04/2009 – 10/2009	Freelance Worker Prof. Dr. Johannes Schaller (SRH Gera)	Gera
09/2008 – 02/2009	Internship at human resources department of Ostsächsische Sparkasse Dresden	Dresden
08/2006 – 10/2006	Internship at Landratsamt Zwickauer Land Sozialpsychiatrischer Dienst	Werdau

Academic education

10/2004 – 09/2009	Chemnitz University of Technology, Chemnitz; Diploma Psychology, focus on occupational psychology and Human Factors Degree: Diploma (final grade 1,1)	Chemnitz
10/2006 – 08/2008	Student assistant at the Professorship of General psychology and Biopsychology	Chemnitz

Teaching

WS 2011/12 – WS 2015/16	Empirical and experimental practical course

Projects

09/2010 – 10/2011	MINI E Berlin V2.0
10/2011 – 03/2012	ActiveE Berlin
04/2012 – 04/2014	Pedelec Naturalistic Cycling Study
01/2013 – 12/2014	Speed perception of two-wheelers
07/2015 –	Rule infringements of bicycle and e-bike riders
08/2015 –	Driver distraction through texting

Award

11/2014	Best Paper Award der 3rd International Cycling Safety Conference for the conference paper: Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J.F., & Gehlert, T. (2014). The German Naturalistic Cycling Study- Comparing cycling speed of riders of different e-bikes and conventional bicycles. *Proceedings of the 3rd International Cycling Safety Conference 2014,* Gothenburg, Sweden.

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Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J., & Gehlert, T. (2015). Speed and safety critical events of cyclists and pedelec-riders – Findings from a naturalistic cycling study. *28th ICTCT Workshop, Ashdod, 28.-30. October.*

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J., & Gehlert, T. (2015). Geschwindigkeit und kritische Ereignisse bei Rad- und Elektrofahrradfahrern verschiedener Altersgruppen.
11. Gemeinsame Symposium der DGVP und DGVM, St. Gallen, 25.-26. September.

Schleinitz, K. (2015). Potentiale zur Erhöhung der Helmtragequote aus psychologischer Sicht. *Expertenworkshop zur Radverkehrssicherheit – Erhöhung der Helmtragequote Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), Berlin, 23. März.*

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Petzoldt, T., Schleinitz, K., Krems, J. F., & Gehlert, T. (2014). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *3rd International Cycling Safety Conference 2014*, *Gothenburg, 18-19. November*.

Schleinitz, K. (2014). Wie schnell und gefährdet sind Elektrofahrrad- und Fahrradfahrer?.
8. Nachwuchsworkshop der Fachgruppe Verkehrspsychologie in der Deutschen Gesellschaft für Psychologie, Chemnitz, Germany, 14.-16. September.

Schleinitz, K., Petzoldt, T., Gehlert, T., Kühn, M., & Krems, J.F. (2014). Drivers' left turn decisions in front of electric bikes and bicycles. In A. Schütz, K. Drewing, & K. Gegenfurtner (Eds.), *Abstracts of the 56th Conference of Experimental Psychologists* (p. 230). Lengerich: Pabst Science Publishers.

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28th International Congress of Applied Psychology, Paris, 8. – 13. July.

Schleinitz, K., Petzoldt, T., Schwanitz, S., & Krems, J. (2013). Pedelec Naturalistic Cycling Study.
Workshop on Naturalistic Cycling Analysis, Gothenburg, 31. August.

EIDESSTATTLICHE ERKLÄRUNG

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe. Die Sprachkorrektur (Englisch) wurde von einem Muttersprachler übernommen.

Katja Schleinitz

Chemnitz, 29.01.2016